ENGINEERING EXPERIMENT STATION
OF THE GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA

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PROGRESS REPORT NO. 1-4

PROJECT NO. A-271

INVESTIGATION OF METHODS FOR MEASURING THE EQUIVALENT ELECTRICAL PARAMETERS OF QUARTZ CRYSTALS

D. W. ROBERTSON

PROJECT DIRECTOR

CONTRACT NO. DA-36-039-sc-71191

DEPARTMENT OF THE ARMY PROJECT: 3-24-02-072
SIGNAL CORPS PROJECT: 867B

APR. 16, 1956-JUNE 1, 1957

CONTENTS

A-271

ENGINEERING EXPERIMENT STATION
of the Georgia Institute of Technology
Atlanta, Georgia

PROGRESS REPORT NO. 1

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I. PURPOSE

The purpose of this project is threefold:

1. To study and investigate methods and techniques for measuring the equivalent electrical parameters of quartz crystal units in the frequency range of 150 to 300 mc/s, including:

   (a) A means for directly measuring the power drive of a crystal unit,

   (b) A simple and practical means of cancelling the capacitance of the crystal unit, C_o, at the test frequency, and

   (c) A means of measuring the effective resistance of the crystal unit at the series resonant condition.

2. To accumulate data from the investigations of 1. above, with a view of utilizing the information for the development of a practical test method for the frequency range 150 to 300 mc/s which will make it possible to:

   (a) Subject the crystal to any selected drive level between the limits of 0.2 and 4.0 milliwatts,

   (b) Measure crystal resistance values between the limits of 20 and 200 ohms,

   (c) Attain an accuracy of resistance measurement of $\pm$ 5 ohms or $\pm$ 10 per cent, whichever is greater, and

   (d) Attain an accuracy of resonant frequency determination within $\pm$ 0.001 per cent of the series resonant frequency of the crystal unit.

3. To study and investigate means for establishing a laboratory measuring technique to be used as a standard for measuring the equivalent electrical parameters of quartz crystal units in the frequency range of 100 to 300 mc/sec.

II. ABSTRACT

The fixed resistors used with present CI Meters are unsatisfactory at higher frequencies because of reactive effects and interpolation requirements. A series of VHF Rheostats was developed under a previous contract which minimized these reactive effects and eliminated the necessity of interpolation. Four similar units of extended frequency range have been constructed under the present contract for use with experimental bridge and substitution type CI Meters. These units complete a set of ten rheostats which exhibit phase angles of less that $\pm 11^{\circ}$ over a range of 30 to 200 ohms from 75 to 300 mc/sec.

A "passive" system, using commercial equipment where feasible, has been chosen for the initial investigation of a possible crystal measurement standard. A setup using presently available VHF signal sources and bridges has been put into operation and experimental data on a number of crystals have been obtained. These data are being utilized in establishing the specifications for the individual items of equipment and in disclosing unforeseen difficulties. No commercial signal generator having the desired stability has been found. However, the Marconi type TF-1066 appears to be the most satisfactory of those available. Frequency synthesizers and variable frequency oscillators are under laboratory study as possible signal sources. A butterfly oscillator has been constructed which indicates a stability at 200 mc/sec comparable to or better than that specified for the Marconi TF-1066. Efforts are being made to obtain individual calibration of the instruments used in order to assure accurate measurements.

A bridge method of measuring crystal parameters with active CI Meter systems was developed under a previous contract. The stray reactances associated with the lumped element construction of this unit imposed an upper frequency

operating limit of approximately 150 mc/sec. A similar unit using a hybrid coaxial configuration and directional couplers is being constructed to reduce or eliminate the reactive effects. Completion of this unit will permit an experimental determination to be made of the possible extension of the upper frequency limit.

Breadboard models of several oscillator circuits have been constructed for use with the bridge system or as a substitution test instrument. One configuration in particular, the Degenerative Plate Oscillator, has shown exceptional promise at frequencies up to and possibly above 280 mc/sec. This unit provides a simple method of preventing oscillations due to the crystal holder capacity and in addition permits one terminal of the crystal to be grounded.

Although questionable because of field distrubances, the voltage across the crystal has been used in the initial measurements to indicate power dissipation. A directional coupler power measurement system is being investigated that appears to be well suited for use with the crystal measurement standard as well as with the proposed coaxial bridge system. A substitution calorimetric power measuring system is also under consideration. This system, which automatically compensates for ambient temperature variations, is reported to have an accuracy of better than one per cent at frequencies near 300 mc/sec.

III. CONFERENCES

Mr. Samuel N. Witt, Jr. visited SCEL on April 3 and 4, 1956 to observe the crystal measurement techniques used by Signal Corps personnel and to discuss the setting up of a laboratory standard at Georgia Tech for precision measurement of VHF crystals.

Mr. Douglas W. Robertson and Mr. Samuel N. Witt, Jr. attended a conference at SCEL on June 28, 1956. The technical status of this project and the future courses of action were discussed. The immediate objectives as outlined under Chapter VII, "Program for Next Quarter," were agreed upon.

IV. METHOD OF APPROACH

This project is sponsored by the Frequency Control Branch of the Signal Corps Engineering Laboratories, Fort Monmouth, New Jersey. The number A-271 was assigned to this project by the Georgia Institute of Technology and work was started on April 16, 1956.

The aim of this investigation is to obtain information concerning new techniques for measuring the equivalent electrical parameters of VHF Crystal Units. Ultimately the information will be used for the development of a practical test instrument which may be used to control the quality of crystal units in production. In this respect it is a continuation, with an enlargement of scope, of the work performed at Georgia Tech during the past two years under contract number DA-36-039-sc-56730.[1]

The present efforts are directed toward two major objectives. The first is an investigation of a method which would be suitable for routine measurement of the necessary parameters to determine crystal quality in the 150 to 300 mc/sec frequency range. The second is an investigation of methods for determining the basic crystal parameters with an accuracy such that the system may be used as a standard of comparison in the 100 to 300 mc/sec range.

Since the first objective requires a simple, easy to use instrument, the approach is directed towards development of an "active" measurement system in which the crystal under test also controls the frequency of the test oscillator. The method for accomplishing the second objective is not necessarily limited as to complexity but should be capable of accurately measuring the various crystal parameters in such a manner that the unit can be completely specified. It appears that "passive" systems are best suited for this purpose because the crystal response can be analyzed at frequencies in addition to those of crystal resonance.

In addition to a review of the literature the efforts for the first quarter have included preliminary work on the following subordinate objectives:

a. Study of methods for measuring crystal power dissipation,

b. Experimental investigation of VHF oscillator circuits suitable for use in "active" substitution or bridge measurement systems with emphasis on configurations which prevent oscillation due to crystal holder capacity,

c. Investigation of hybrid coaxial bridge systems for use with "active" oscillator circuits,

d. Construction of VHF Rheostats of extended frequency range,

e. Experimental study and comparison of various "passive" measurement systems using commercial signal sources and bridges,

f. Laboratory study of frequency synthesizers and investigation of construction possibilities of stable variable-frequency-oscillators for use as a signal source for "passive" measurement systems, and

g. Preliminary measurement of VHF crystals using "passive" systems.

V. EXPERIMENTAL WORK AND CIRCUIT STUDIES

A. VHF Rheostats

1. Introduction

VHF crystal units capable of providing direct crystal control in the 100 to 150 mc/sec frequency range are presently available and the advent of units operating up to 300 mc/sec is evident. Developmental units and modified versions of the presently used Crystal Impedance Meter TS-683/TSM have been employed to measure crystal units at frequencies up to 200 mc/sec.[1,2] Efforts are presently being directed toward development of similar units with frequency ranges up to 300 mc/sec.

These devices, which are essentially "active" oscillators, utilize a substitution method whereby the frequency and amplitude of oscillation remains unchanged when the proper substitution resistor is inserted in place of the crystal unit. When this condition is met, the oscillator is operating at the crystal resonant frequency and the substitution resistor is equal to the equivalent resonant resistance of the crystal unit. The accuracy of this method depends largely on the phase angle characteristics of the substitution resistors. It has been shown that for crystals having Q's of 10,000 or greater the substitution resistor must exhibit a phase angle, at the crystal frequency, of less than $\pm 11^{\circ}$ in order to obtain a measured frequency that is within ± 0.001 per cent of the crystals true (zero phase angle) series resonant frequency.[2]

2. Experimental Rheostats

The calibration resistors provided as substitution elements with the TS-683/TSM are unsatisfactory at the higher frequencies because the distributed reactive effects give rise to excessive-phase-angle characteristics. In addition, these resistors are fixed and interpolation is required between successive resistors for many parameter measurements. To overcome these limitations a series of variable VHF Rheostats was developed at Georgia Tech which minimized the reactive effects and eliminated the necessity of interpolation.* Compensation of the remaining reactive effects was incorporated so that only a few units were required to cover the range of 20 to 200 ohms from 75 to 200 mc/sec with acceptable phase characteristics.[1]

Since the experimental efforts of the present work require similar units covering an extended frequency range, additional rheostats were constructed using the same principle and configuration. Basically the rheostat consists of a metallic-film resistive element, a collector bar and a wiper arm physically arranged so as to minimize the distributed reactance. Electrical connections to the collector and resistive elements are brought out through the base of the unit and attached to the pins of a HC-6/U holder base which is employed to facilitate use of the rheostat when making crystal tests. A view of a disassembled unit showing the arrangement of the principal parts is shown in Figure 1. Compensation of the remaining reactive components is incorporated in the lower resistance units by the addition of a series capacitor. Figure 2 shows an assembled unit and the placement of the compensating capacitor.

Five rheostats are required for the frequency range of 200 to 300 mc/sec with a phase angle limitation of $\pm 11^{\circ}$. Four rheostats are compensated for the resistance range of 30 to 80 ohms, each covering a frequency increment of

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*Patent pending No. 586,945

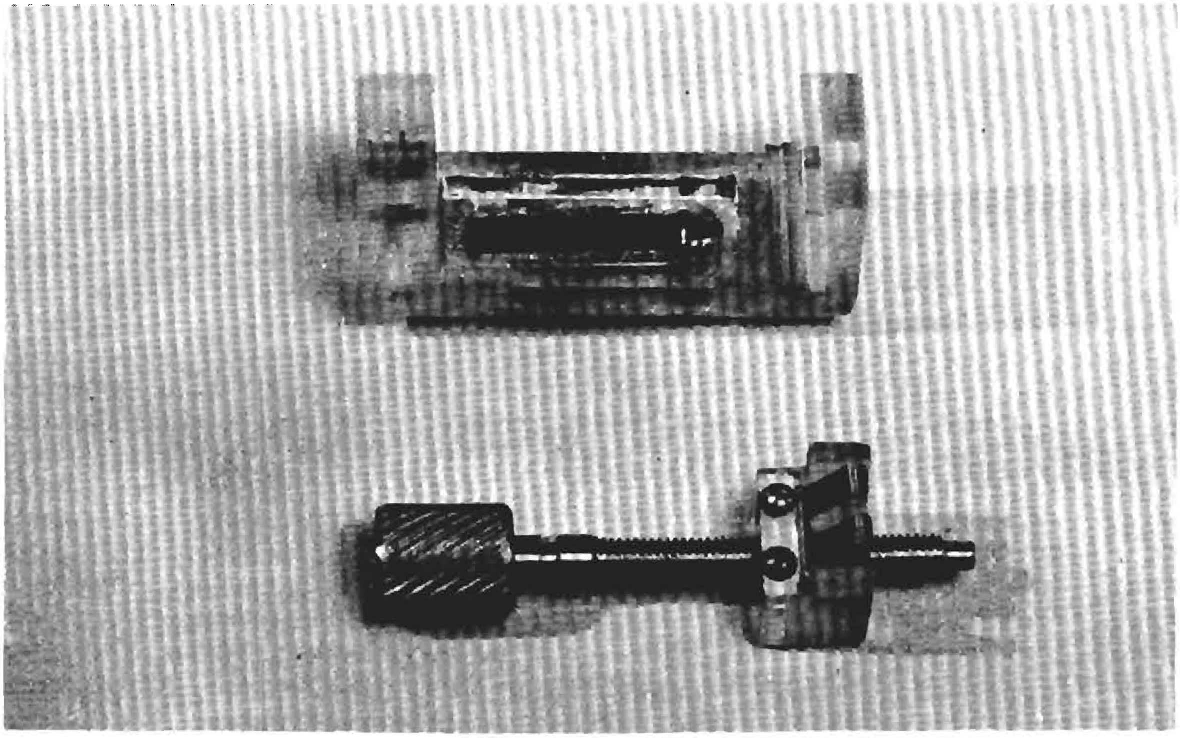

Figure 1. Disassembled VHF Rheostat.

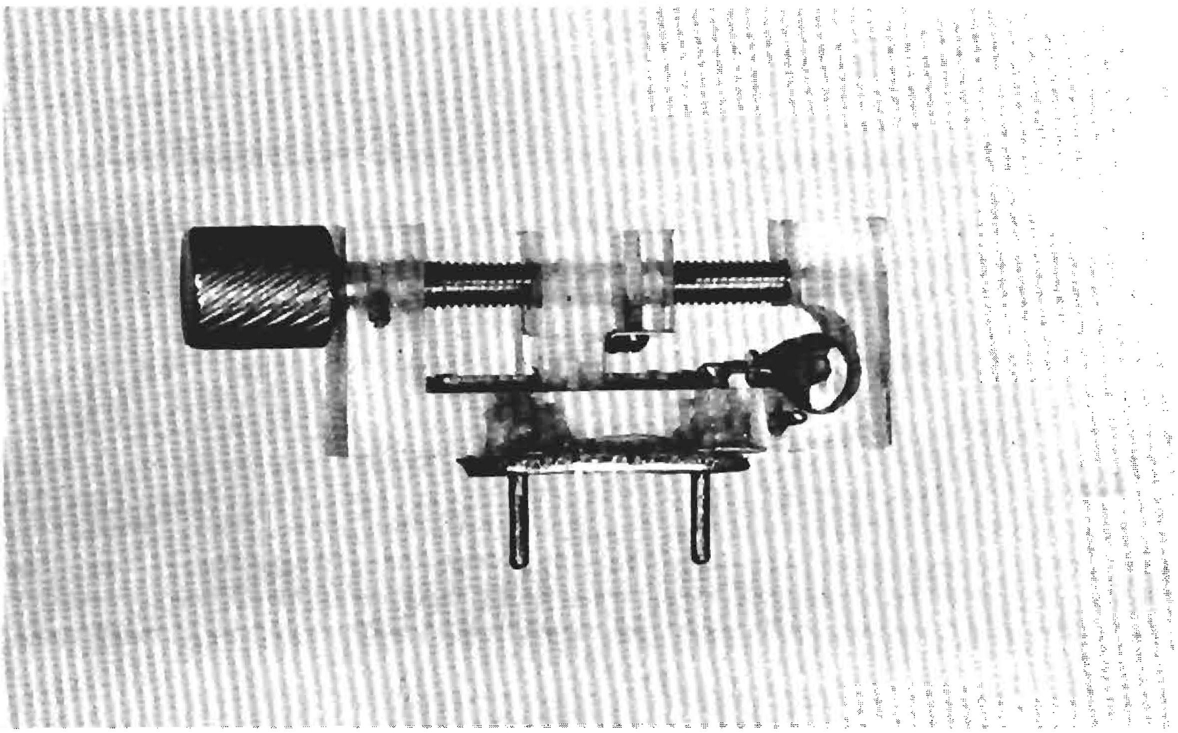

Figure 2. Series Compensated VHF Rheostat.

25 mc/sec. Representative curves of the phase angle characteristics of these units are shown in Figure 3a through 3d. The fifth unit is uncompensated and may be used over the frequency range of 75 to 300 mc/sec for resistance values from 80 to 200 ohms. Figure 3e shows the phase angle characteristics for this unit. Since it is doubtful that any crystal units above 200 mc will be available which exhibit equivalent resistances below 30 ohms, no attempt was made to obtain satisfactory phase compensation below this value. However, such compensation can be obtained by reducing the frequency increments which would increase the number of rheostats required.

B. Crystal Measurements Standard

1. Introduction

Crystal measurement systems may be classified in several ways. One such classification is based on the source of excitation. In "active" systems the crystal is driven by an oscillator whose frequency is controlled by the crystal itself while in "passive" systems the crystal is driven by an oscillator whose frequency is completely independent of the crystal being measured. The latter method of control has been chosen for the laboratory standard to give greater versatility and greater freedom from possible interactions between the crystal being measured and the source of radio frequency energy.

It is desirable in so far as possible to use commonly available equipment in constructing the standard so that the setup may be readily duplicated. Because of the accuracy requirements, severe limitations are placed on the choice of equipment. Systems using VHF bridges, standing wave lines and other principles have been considered. The VHF bridge configurations appear to be the most desirable because of the method of data presentation and the accuracy obtainable.

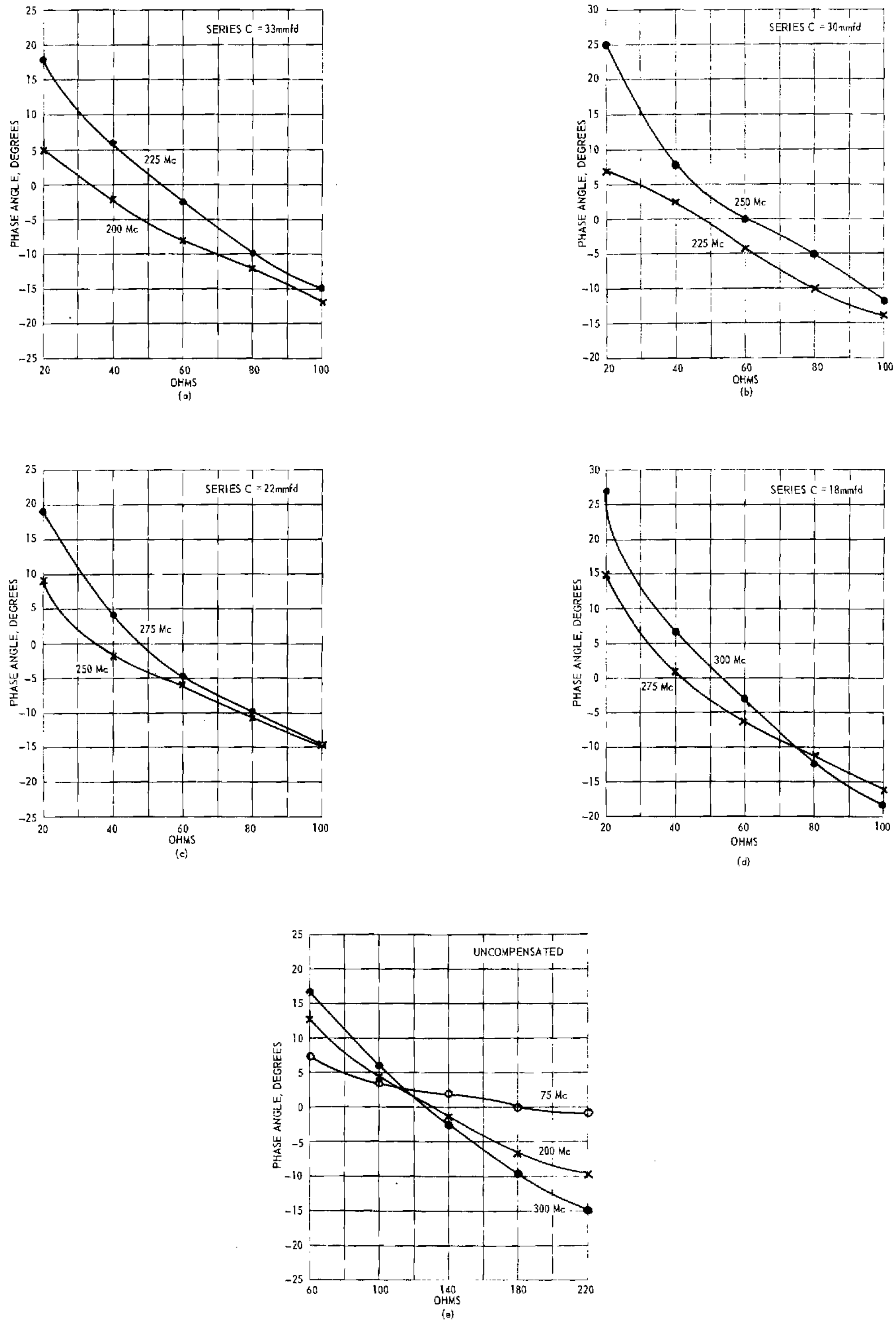

Figure 3. Characteristic Phase-Angles of the VHF Rheostat.

The fact that most bridges operate on a null principle also makes them desirable. The use of bridges also permits the complete circle diagram of the crystal to be obtained. This is desirable in that it provides a method of self-checking the individual points on the curves.

The two most commonly used VHF bridges are the Hewlett-Packard Model 803A VHF Bridge and the General Radio Type 1602 UHF Admittance Meter. Both of these instruments are reasonably accurate over the frequency range from 100 to 300 mc. The Hewlett-Packard Bridge appears to be the more desirable of the two instruments because of slightly greater accuracy when properly corrected, better scale resolution and more convenient presentation of data. However, the Admittance Meter requires a less sensitive null detection system. Both instruments have been used in the preliminary laboratory setup.

The choice of a radio frequency signal source is one of the major problems involved in setting up the laboratory standard. It has been estimated that a stability of at least one part per million for periods of time of one minute is desirable for efficient measurements. No commercial signal generator having this stability has been found. Various signal generators, including the Marconi Type TF-1066 are, however, under consideration. Measurements to date have been made with the Hewlett-Packard Model 608A generator. This instrument is usable only with extreme difficulty. The construction of a signal generator by project personnel is contemplated and will be discussed in section B.3 of this chapter.

Other points of interest concerning the laboratory standards include calibration of instruments, measurement of drive level, method of presentation of data and analysis of data. Some of these points will be discussed at appropriate places in this report.

2. Experimental Data

The experimental data obtained thus far is of interest since it is from this data that the specifications for individual pieces of equipment has been derived.

A block diagram of the initial laboratory setup is shown in Figure 4.

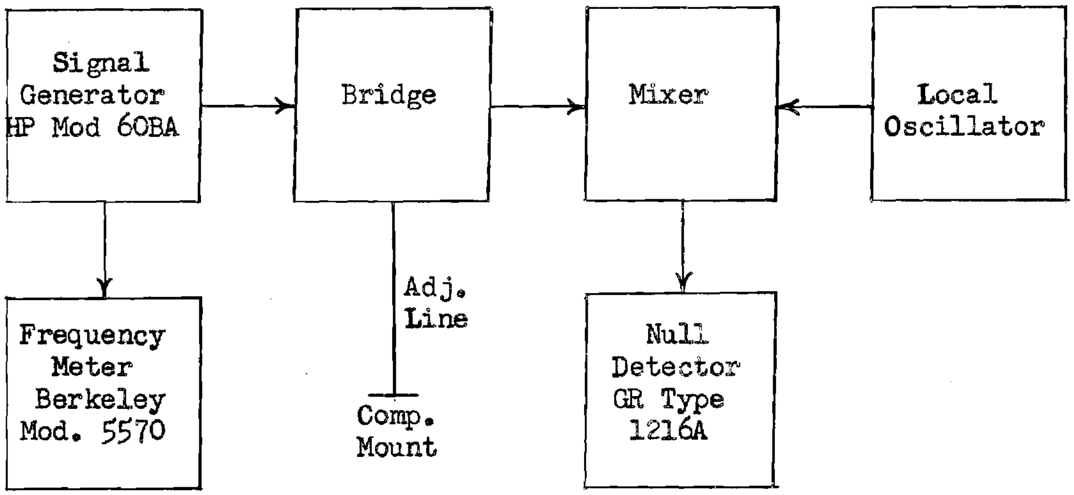

Figure 4. Block Diagram of The Initial Laboratory Setup.

A total of 32 circle diagrams have been run on 12 VHF crystals at frequencies of 118 mc to 185 mc. The General Radio Admittance Meter was used for 27 of the curves and the Hewlett-Packard VHF Bridge for 5 of the curves. When the VHF Bridge was used it was necessary to replace the mixer, local oscillator and null detector by a sensitive VHF receiver to obtain adequate null detection sensitivity. Since the receiver was available only on a loan basis, extensive data using the VHF Bridge could not be obtained.

Some of the curves which have been obtained are shown in Figures 5 through 11. These curves were chosen to show some of the difficulties which have been experienced and are not the curves which show the best agreement.

The setup for obtaining Figure 5 was as shown in Figure 4 using the GR Admittance Meter. The line to the component mount was adjusted to one-half wavelength at the crystal frequency. The power was adjusted to two milliwatts as indicated by voltage measurements across the crystal. The points were read consecutively around the circle. The time required to obtain all of the readings was about 45 minutes. This curve has been duplicated on other occasions with very close agreement. A true circle is drawn through the points in this figure.

Figure 6 presents data on the same crystal as obtained with the VHF Bridge. A half-wavelength line was also used to obtain this data. A Servo Corporation of America receiver was used as the null detector. Additional crystal modes are also shown in this figure. The data for Figure 6 agrees reasonably well with that of Figure 5 except for an angular error which may be accounted for as a half-wavelength line adjustment error. The curve showing the principal mode is not the one that best fits the points but is instead the circle obtained in Figure 5.

Figure 7 was obtained with the same setup as for Figure 5 except that the component mount was mounted directly on the Admittance Meter without the half-wavelength line. Figures 5 and 7 should agree except for a rotation factor; however, a distortion in the form of a flattening is shown on Figure 7. The cause of this flattening has not yet been found. Similar flat spots have appeared on curves for other crystals. It may be noted that the minimum impedance point does fall on the circle as transposed from Figure 5 and corrected for line length. It is interesting to observe that Figure 7 may be drawn as

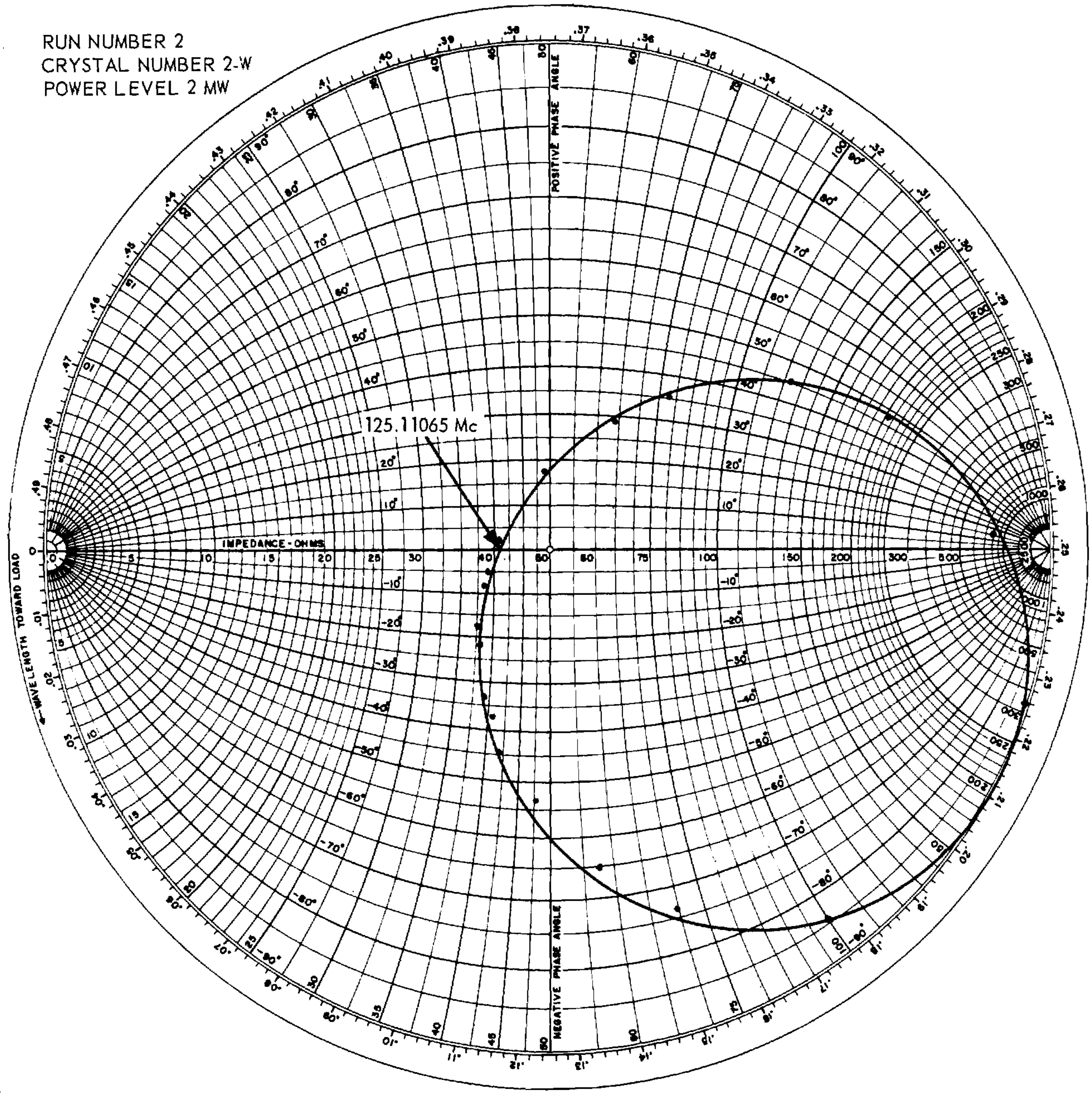

Figure 5. Crystal No. 2-W Measured with the GR Admittance Meter.

RUN NUMBER 23
CRYSTAL NUMBER 2-W
POWER LEVEL 2 MW

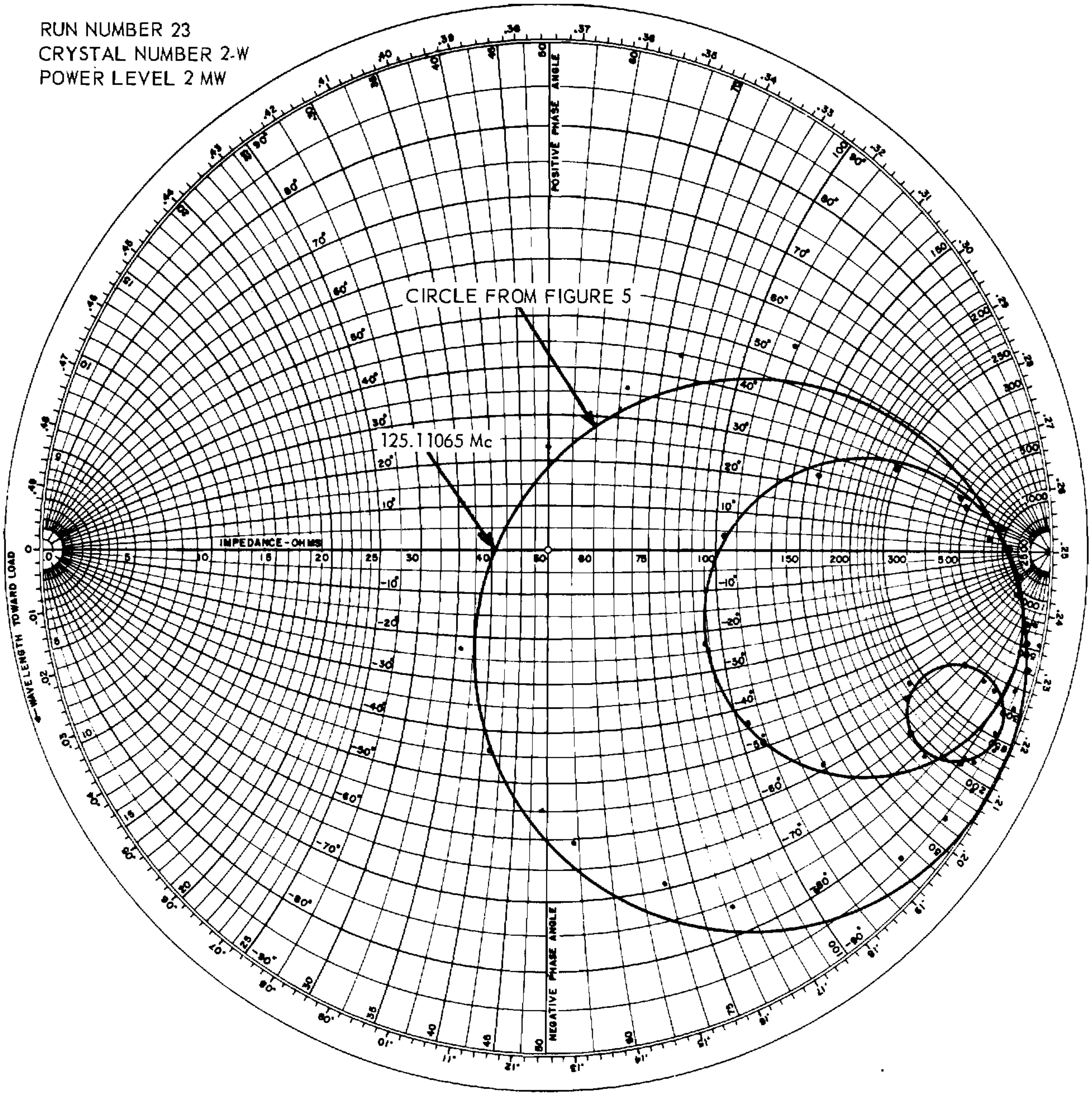

Figure 6. Crystal No. 2-W Measured with the HP VHF Bridge.

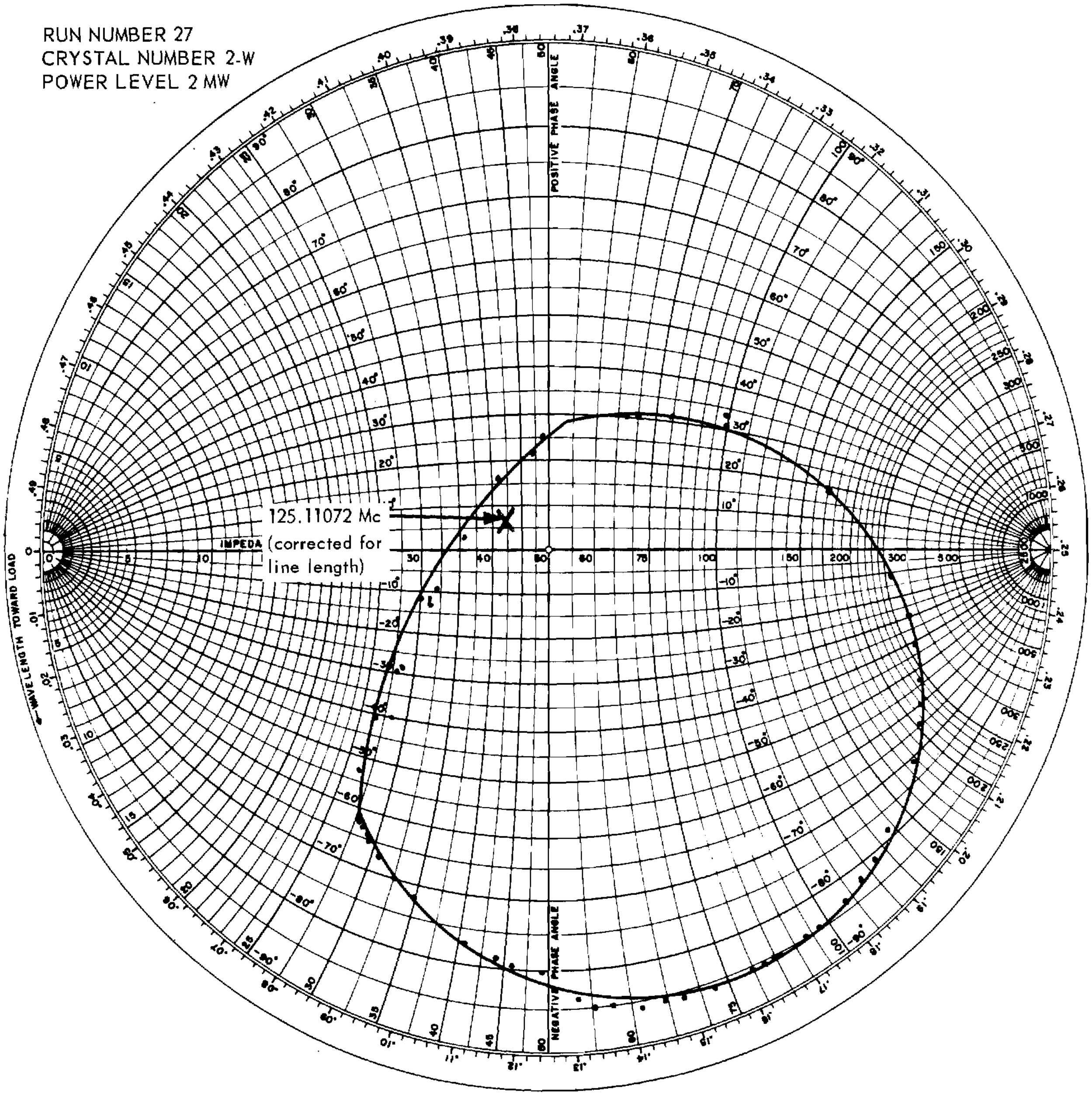

Figure 7. Crystal No. 2-W Measured with the GR Admittance Meter and without the Half-Wave Line.

two circular sections. The frequency readings at zero phase angle agree within ten cycles per second for Figures 5 and 6 and within 70 cycles per second for Figure 7.

Figures 8 through 11 were all obtained for the same crystal and overtone. Figure 8 was obtained using the VHF Bridge while Figures 9, 10 and 11 were obtained using the Admittance Meter. The half-wavelength line was used for all measurements. In an attempt to determine the cause of the flattening in Figure 9, the susceptance capacity standard on the Admittance Meter was adjusted to 135 mc to obtain Figure 10 and to 115 mc to obtain Figure 11. It may be observed that Figure 10 is the more nearly perfect circle of the curves obtained with the VHF Bridge. This indicates that the Admittance Meter and its accessories may possibly be out of adjustment sufficiently to cause some of the distortion in Figure 9. Any errors in susceptance values alone cannot account for all of the distortion since the impedance magnitudes at zero phase angle differ by ten per cent for Figures 8 and 9. The frequency readings at zero phase angle agree within 400 cycles per second for all four curves. Three of the curves agree within 200 cycles per second.

All of the curves show some randomness of points. This was caused primarily by the difficulty in properly setting and maintaining the frequency while a reading was being made. It has also been observed that the disagreements between the Admittance Meter readings and the VHF Bridge readings have not always been consistant, i.e., in the same direction.

The experience gained from the initial measurements have led to the following conclusions concerning requirements for a suitable laboratory standard:

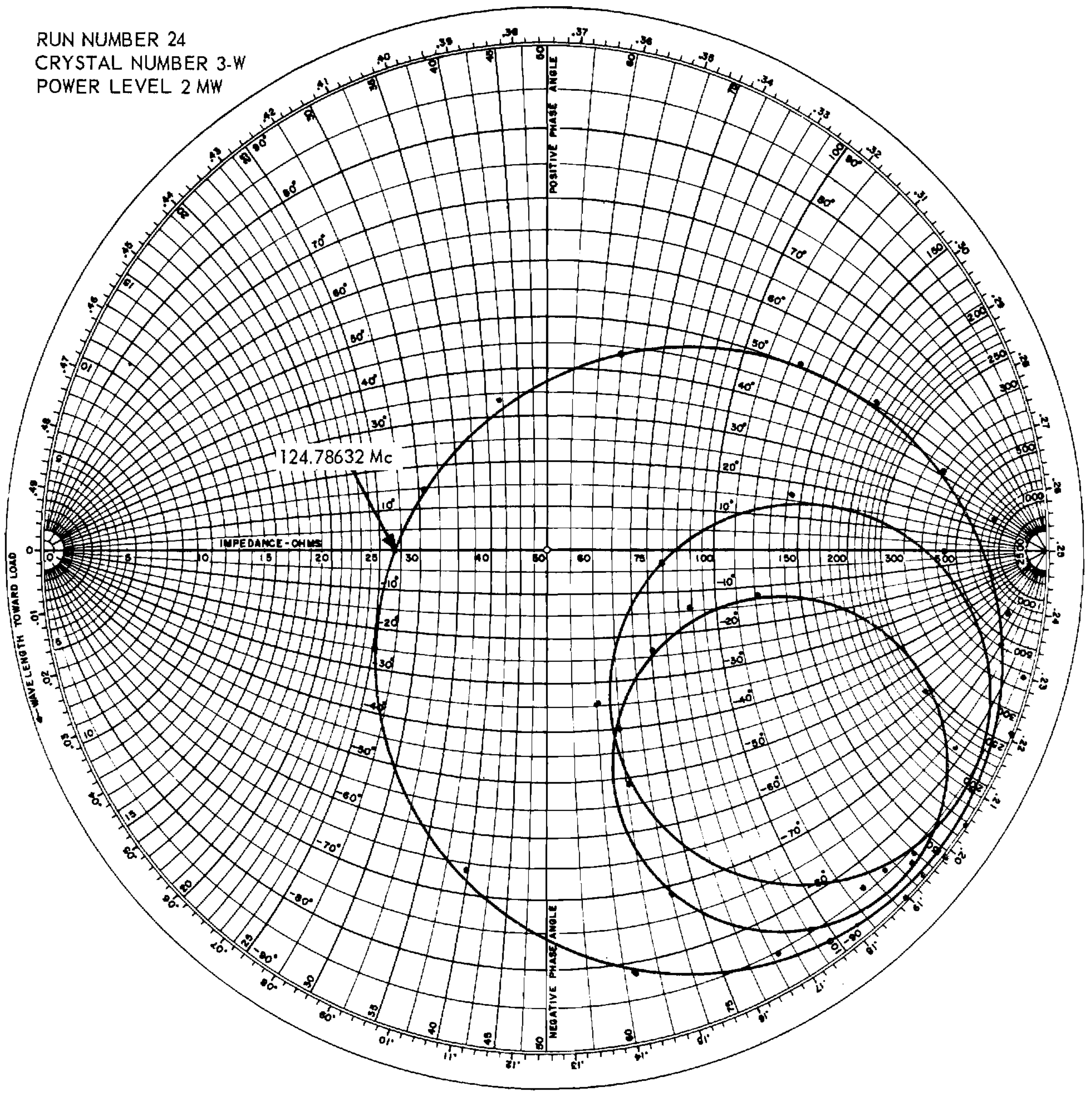

Figure 8. Crystal No. 3-W Measured with the HP VHF Bridge.

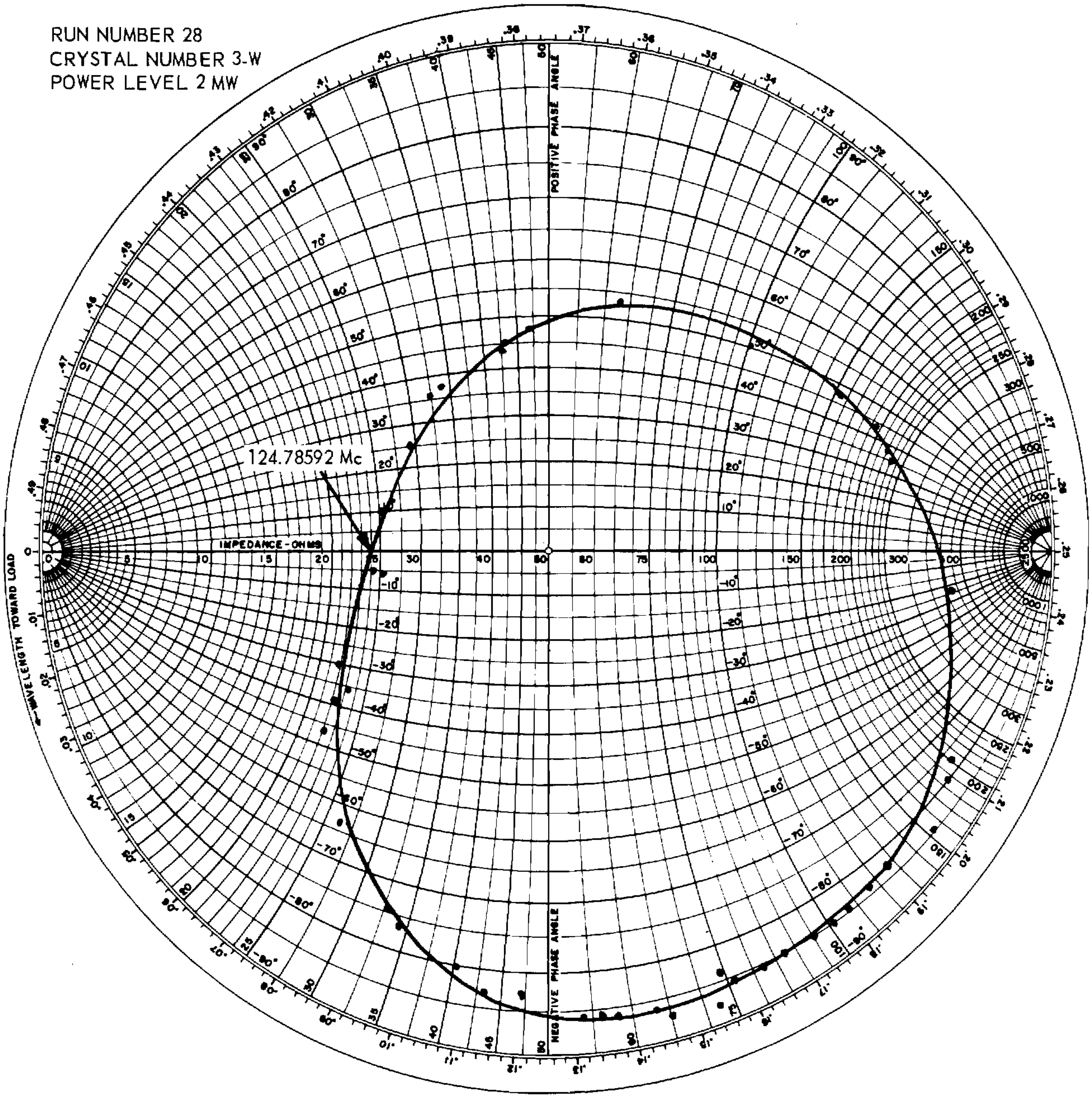

Figure 9. Crystal No. 3-W Measured with the GR Admittance Meter.

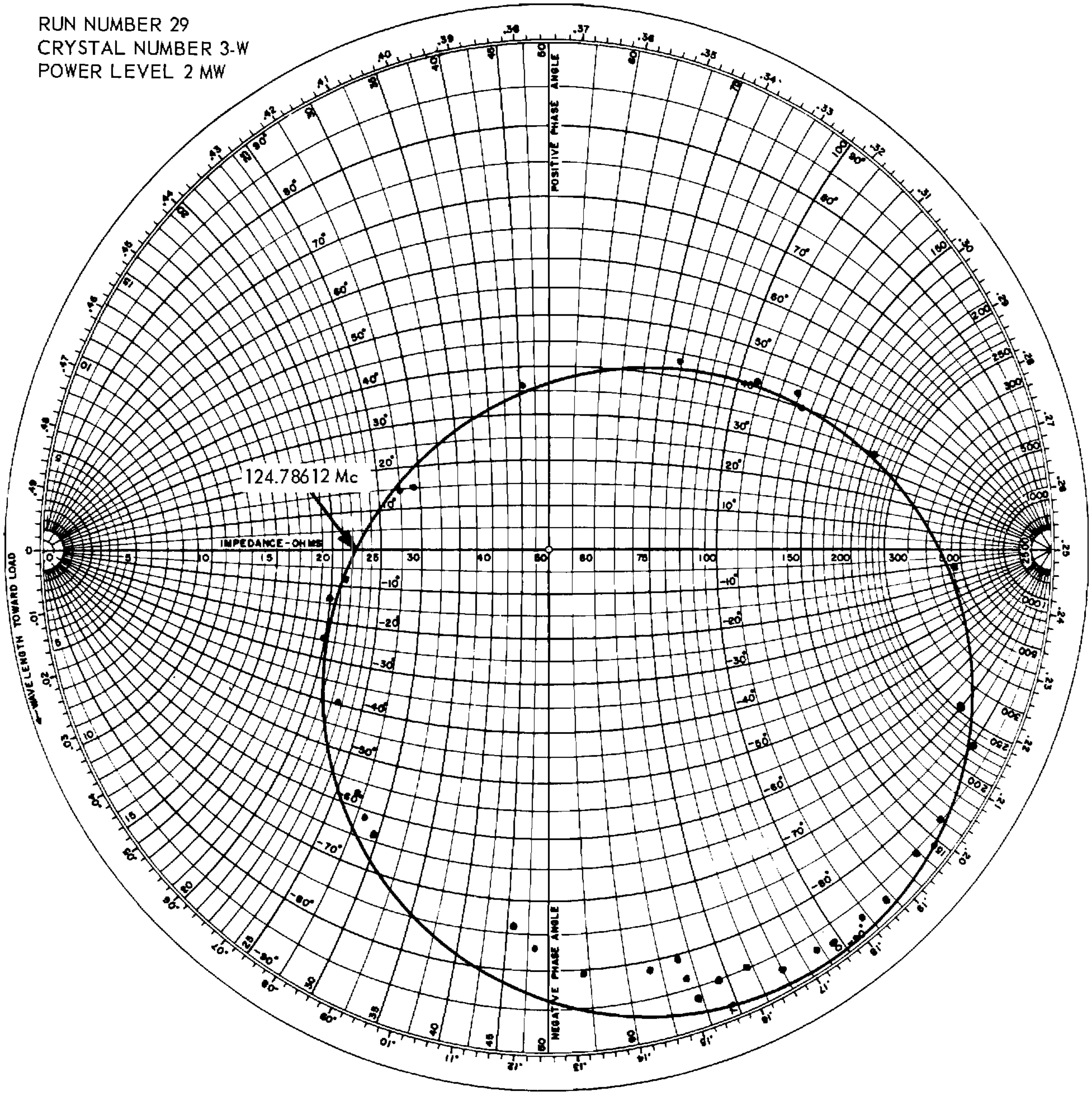

Figure 10. Crystal No. 3-W Measured with the GR Admittance Meter and with the Susceptance Standard Set at 135 Mc.

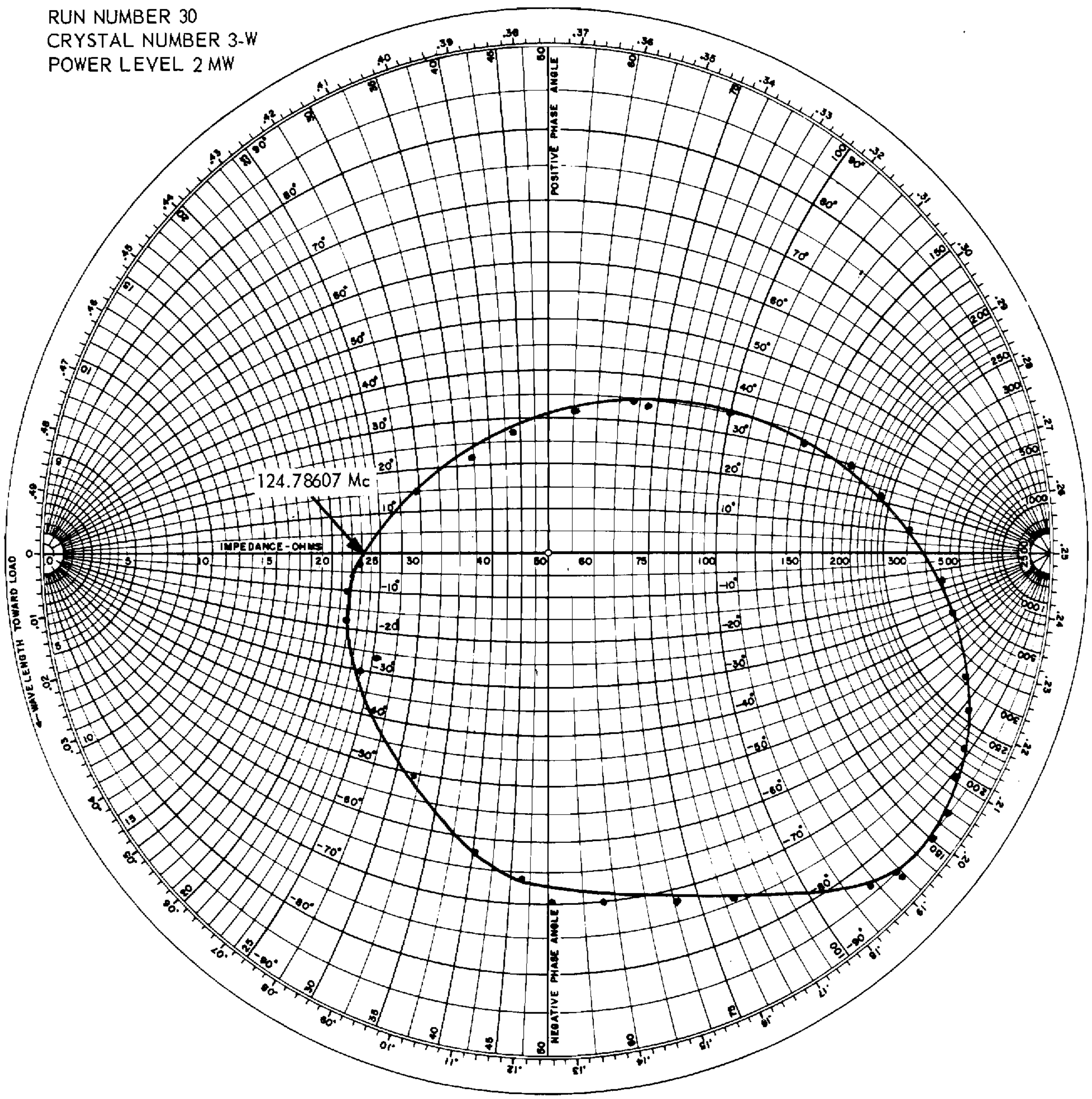

Figure 11. Crystal No. 3-W Measured with the GR Admittance Meter and with the Susceptance Standard Set at 115 Mc.

a. It is necessary that a more stable signal source be obtained before further analysis of the problems can be made.

b. The effects of line lengths and line corrections must be studied in detail.

c. All instruments used must be calibrated to greater accuracy.

d. An improved detector system must be purchased or developed to permit effective use of the VHF Bridge.

e. A more accurate power measurement procedure must be developed since power differences could account for some of the discrepancies noted.

After a laboratory standard has been developed to meet these requirements, remaining problems such as distortion of the circle diagrams can be studied in more detail. It is, of course, probable that complete circle diagrams will not have to be plotted in the eventual laboratory standard in order to obtain sufficient information on the crystals under test. It is presently believed, however, that the complete circle diagram gives a more accurate check of all parameters than discrete frequency measurements would.

3. Stable Signal Generators

The investigation of sources of stable radio frequency energy has been conducted in two directions: to locate and obtain a suitably stable commercial generator and to design and build a suitable generator.

The first approach has led only to limited success. Of the many laboratory generators available, only three approximate the requirements. The Rohde and Schwarz Type XUA Frequency Synthesizer has more than adequate stability but would require frequency multiplication since its highest output frequency is

30 mc. It would also be prohibitively expensive for the project to purchase. The Lavoie Frequency Meter Model LA-6 could possibly be used; however, it suffers from very low output voltage (50 microvolts) as well as spurious responses. The difficulty in obtaining sufficient output at a single frequency could limit its usefulness. The Marconi Type TF-1066 Signal Generator appears to have suitable specifications, but earliest delivery has been quoted as more than three months even for a sample unit which could be placed on test.

The alternative to buying a commercial generator is to design and build a unit in the laboratory. Several possible types of signal sources are under consideration or under test. A butterfly oscillator has been constructed to provide frequencies from 140 mc to over 400 mc. Although the initial stability was poor, modifications have resulted in an oscillator of reasonable stability. Figure 12 shows the frequency variations of this oscillator at a frequency of 200 mc. It can be seen that periods as great as four minutes exist where the frequency remains within one part per million. This oscillator has not yet been stabilized against temperature variations. The stability of the supply voltage can also be improved considerably. Isolation amplifiers and attenuators have not yet been added to the oscillator.

Another type of oscillator under consideration is the cavity configuration. No construction has yet been started, but preliminary design calculations indicate that adequate stability might be obtained. One difficulty of wide-frequency-range cavity oscillators is that the drift rate often increases considerably when the frequency is changed by a relatively large amount. This is usually due to changes in heat dissipation within the cavity, especially if the tube is mounted within the cavity walls. The initial warm-up time for cavity oscillators is also fairly great.

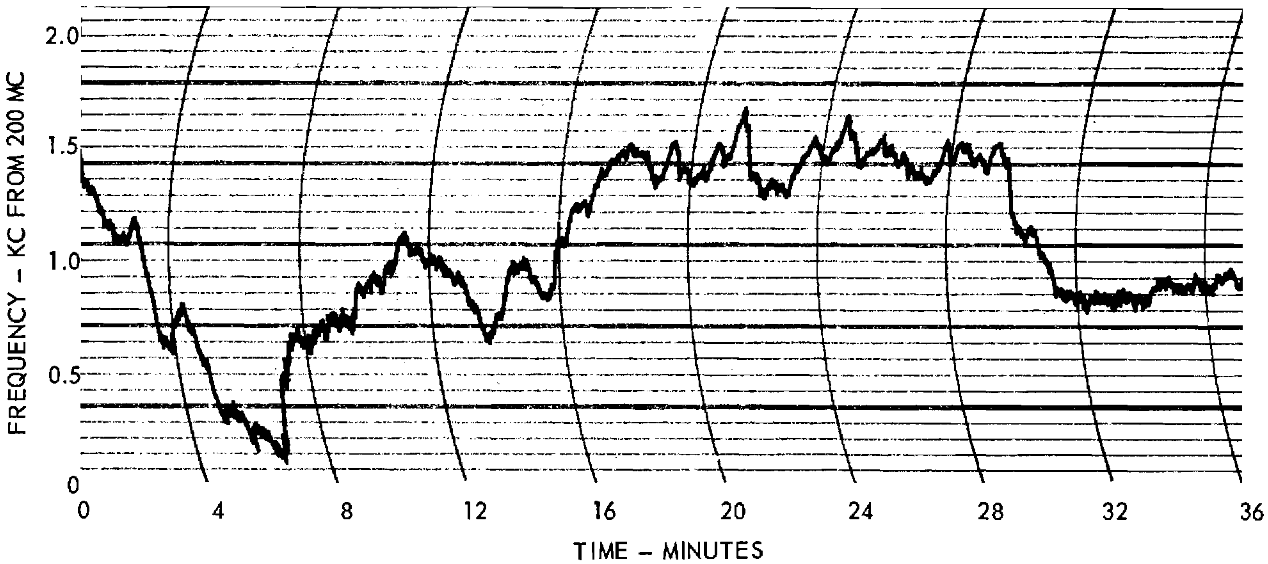

Figure 12. Frequency Variations of the Butterfly Oscillator.

A third configuration under consideration is one which depends on crystal control for the basic stability. A block diagram of one such system is shown in Figure 13.

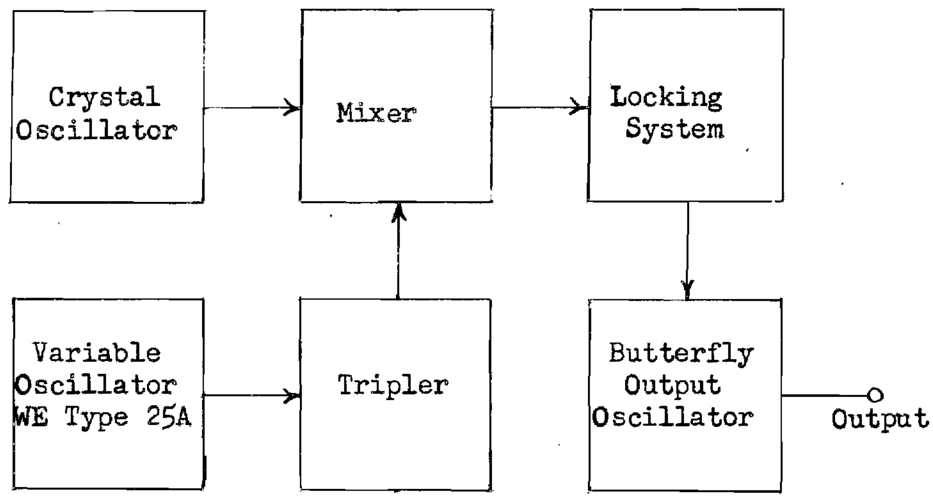

Figure 13. Crystal Stabilized Signal Source.

The Western Electric Type 25A Interpolation Oscillator, a variable frequency 11-15 mc oscillator, was chosen because of its unusually good stability. The output of this oscillator is tripled to provide a 10-mc span and then mixed with a series of frequencies obtained from a crystal oscillator. The crystal controlled frequencies would be spaced at 10-mc intervals. The mixing results in three output frequencies: the crystal oscillator frequency, the crystal frequency plus the variable frequency, and the crystal frequency minus the variable frequency. Either of the latter two frequencies may be used to provide a locking signal for the butterfly output oscillator. Thus a continuous coverage of the frequencies from 100 to 300 mc may be obtained. The crystal oscillator as shown would require a set of 13 crystals from 140 to 260 mc spaced at approximately 10-mc intervals. This oscillator could, of course, be replaced by a single 10-mc oscillator with suitable harmonic generators. The locking system may be a simple injection system or may require a more complicated circuit involving a reactance tube control.

4. Detector Systems

As mentioned earlier, the detector system shown in Figure 1 is inadequate because of insufficient sensitivity for use with the VHF Bridge. This detector system also produces spurious responses which are undesirable. The purchase of a laboratory receiver has been considered; however, no single receiver has been found which has adequate sensitivity, sufficiently small leakage and the proper frequency coverage. A Type AN/APR-4 receiver is available for use by the project but it is not equipped with the proper tuning unit. Thus, an attempt is being made to locate a Type TN-17 (76-300 mc) tuning unit. With this tuning unit, the receiver would be suitable for use as a detector as well as a spectrum analyzer for determination of spurious responses. The receiver has a 30-mc i-f output which can be used with an external i-f amplifier for increased sensitivity.

5. Calibration of Instruments

After a satisfactory laboratory measurement system has been completed, a remaining problem will be the absolute calibration of the instruments. Frequency measurement is no problem because of the availability of accurate standards. The accuracy of impedance measurements will depend directly upon the calibration of the instruments used. Since the claimed accuracies of the General Radio Admittance Meter and the Hewlett-Packard VHF Bridge are less than that required, it will be necessary to obtain individual calibration of the instruments used. Letters have been written to General Radio Company and to the National Bureau of Standards to obtain more information concerning the accurate calibration of these instruments. It is also planned to obtain accurate calibration of several fixed impedances so that the calibration of the bridges may be checked periodically.

C. Experimental CI Meter

1. Introduction

A configuration, called the Crystal Parameter Bridge, was developed under a prior contract.[1] This device enabled all the fundamental equivalent circuit parameters of a quartz crystal to be measured. The system utilized an active oscillatory circuit and the bridge in such a manner as to allow the crystal being measured to also control the frequency stability of the oscillator. The bridge was used in the oscillator in a manner such that when the oscillator was tuned at or near one of the crystal resonant frequencies it was stabilized by the increased portion of the feedback passing through the crystal arm of the bridge. The resulting combination allowed measurement of the fundamental parameters and combined many of the desirable properties of both the passive and active measuring systems. The bridge as developed was of lumped element construction and, as in conventional bridges, the distributed reactances limited the useful application to frequencies below 150 mc/sec. An additional limitation that occurred above 150 mc/sec was due to the crystal holder capacity, C_o, and the associated bridge balancing capacity. The reactances of these capacities decreased at the higher frequencies until crystal control could no longer be obtained.

It appears that these limitations can be overcome and the bridge principle extended for use at the higher frequencies. Since the oscillatory circuit used in conjunction with the bridge can possibly be used alone as a substitution type test set (CI Meter), the work has been broken down into two convenient tasks: the development of a VHF Crystal Parameter Bridge and the development of a suitable VHF oscillator.

2. Experimental Bridge

A hybrid coaxial bridge is being constructed which should surmount the limitations caused by the stray reactance of the lumped element bridge. As shown in Figure 14 this device will utilize two matched directional couplers to sample a portion of the current flowing through each branch of the bridge. These two samples are then compared in a sensitive null indicator. Adjustment of the oscillator frequency and the resistance (VHF Rheostat) and/or capacitance of the non-crystal branch allows a null condition to be reached and the various crystal parameters to be determined in the same manner used for the lumped element bridge.

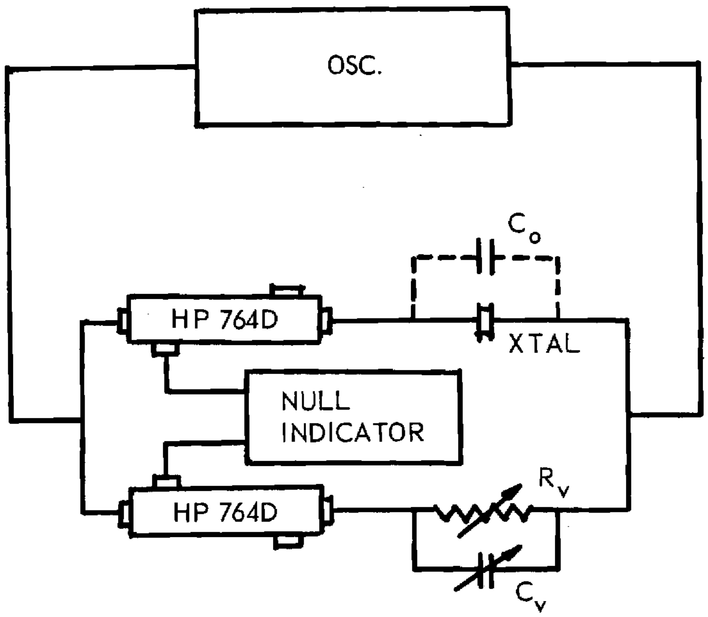

Figure 14. Hybrid Coaxial Bridge.

Two VHF dual directional couplers, Hewlett-Packard 764D, are on order for use in the system described. Arrival of these units will permit an experimental determination to be made of the feasibility of using the coaxial bridge system with presently available oscillator circuits.

3. Experimental Oscillators

In addition to the usual requirements, an oscillator circuit suitable for use with the bridge system or as a substitution test instrument should meet the following requirements:

a. Be capable of oscillation over as wide a frequency range between 150 to 300 mc/sec as possible,

b. Be capable of oscillation with equivalent crystal resistances up to 200 ohms,

c. Provide for external control of level of oscillation,

d. Exhibit adequate amplitude stability at low and high levels of crystal dissipation,

e. Incorporate resonant circuits external to the crystal having sufficient selectivity to reduce harmonic content to a negligible minimum,

f. Maintain crystal control frequency that is relatively insensitive to detuning of external resonance circuits,

g. Utilize a configuration whereby one terminal of the crystal unit is grounded, and

h. Prevent or reduce any oscillations resulting from the crystal holder capacity C_o.

Although not necessarily first in relative importance, the requirements of items g and h have received major emphasis in considering possible circuit configurations. Since the proposed bridge system uses coaxial components having the outer conductor grounded, the desirability of operating the crystal with one terminal grounded is evident. Furthermore this allows the crystal, the VHF Rheostat and the C_o balancing capacitor to be used as two terminal devices. Use of these units in a bridge system which requires both terminals to be above ground leads to equivalent four terminal devices and the distributed reactances greatly increase the difficulty of constructing a symmetrical bridge.

Breadboard models of several oscillator configurations which allow one terminal of the crystal to be grounded have been constructed. Figure 15 shows the schematic of a modified version of the common cathode coupled circuit.

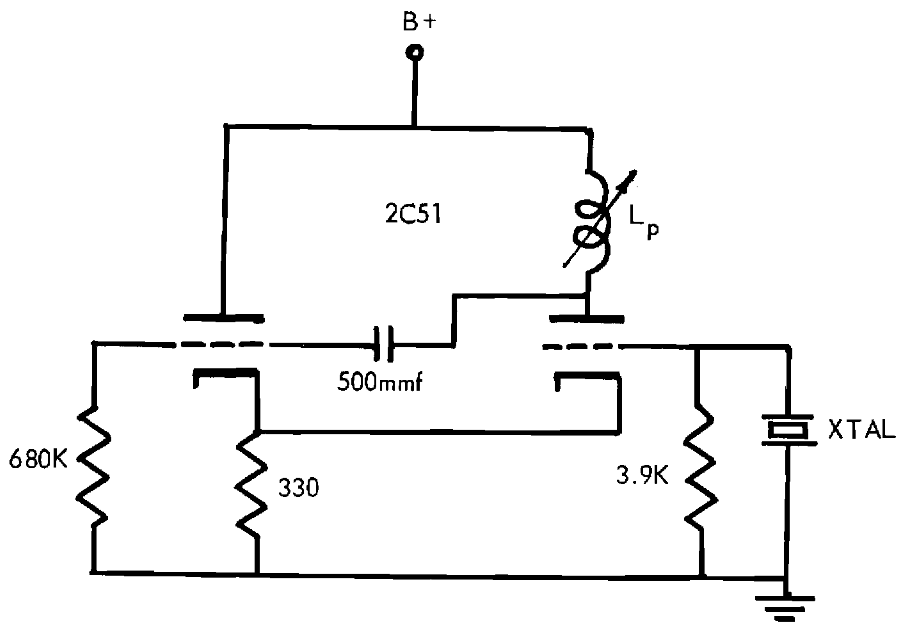

Figure 15. Modified Cathode Coupled Oscillator

The gain of the grounded grid stage is normally reduced since the grid is raised above ground by the high impedance of the crystal at frequencies away from resonance. Near or at resonance the grid is effectively grounded through the low equivalent crystal resistance, and oscillations take place. The experimental units using a Mallory Spiral Inductuner section for L_p operated at frequencies up to 240 mc/sec with substitution resistors in excess of 100 ohms. The oscillator indicated no tendency to free run as oscillations were not obtained at any setting of L_p when the substitution resistor was removed. Experimental checks using crystals have not as yet been made except to determine the necessity of cancelling the crystal holder capacity. This was evident in that the circuit oscillated on C_o when the crystal units were tried.

In both the bridge and substitution systems as well as in "use" oscillators the reactance of the crystal holder capacity, C_o, decreases with increased frequency until a point is reached where C_o provides a path through which uncontrolled oscillations take place. This effect can be eliminated by connecting an inductance across the crystal unit which antiresonates the holder capacity at the crystal frequency. However, this imposes stringent requirements on the inductance at frequencies above 150 mc/sec in that it is difficult to construct or obtain variable units in the 0.01 to 0.1 microhenry range. The capacitance bridge oscillator provides another method of eliminating the effects of C_o.[3] As shown in Figure 16 an equal out-of-phase voltage is fed through a capacitor equal to C_o in a manner such that the signal due to C_o is effectively cancelled. This system appears desirable in that the capacitive balance is not critical when used with the bridge measurement systems. Only partial cancellation is required to reach a condition such that the loop gain is insufficient to maintain oscillation. One disadvantage of previously proposed systems results from the use of a tapped transformer. Such transformers covering wide tuning ranges above 150 mc/sec are difficult to construct. The location of the crystal unit such that neither terminal is grounded presents an additional disadvantage when used with the bridge measuring system.

One configuration using the capacitive bridge principle but eliminating the above difficulties is being investigated on an experimental basis. Figure 17 shows a simplified schematic of this circuit which uses a differential amplifier in place of the tapped transformer. Furthermore, this method allows grounding of one terminal of the crystal unit. Although a complete experimental determination of the usefulness of this circuit has not as yet been made, it appears worthy of additional investigation.

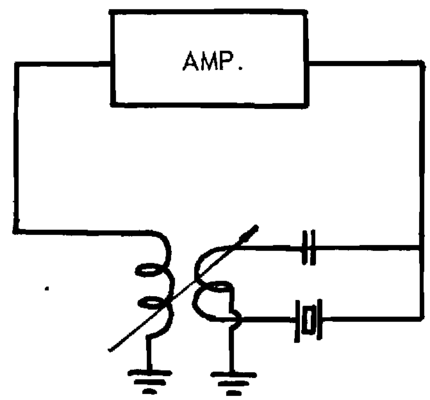

Figure 16. Capacitance Bridge Oscillator

Figure 18 is the schematic diagram of another version of the cathode coupled oscillator which allows the crystal to be grounded and also provides a simple method of preventing oscillations due to C_o. In this circuit the crystal holder capacity is resonated with the inductance L_1 and provides a high plate impedance for the cathode follower section. This impedance reduces

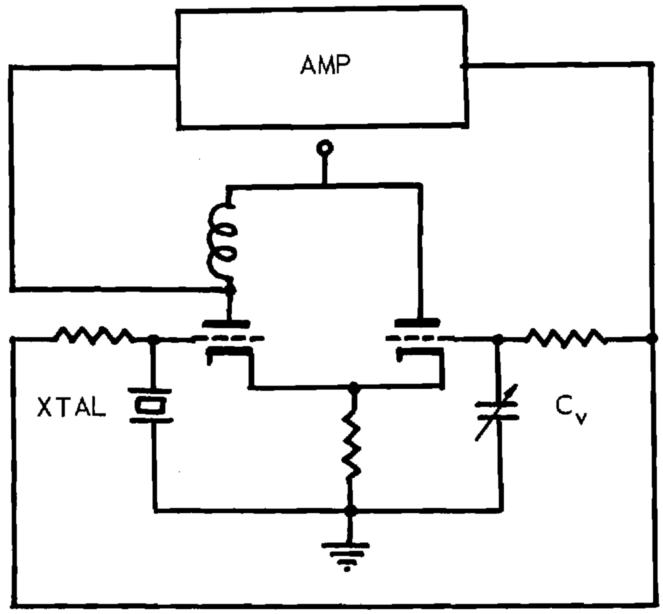

Figure 17. Differential-Amplifier Oscillator.

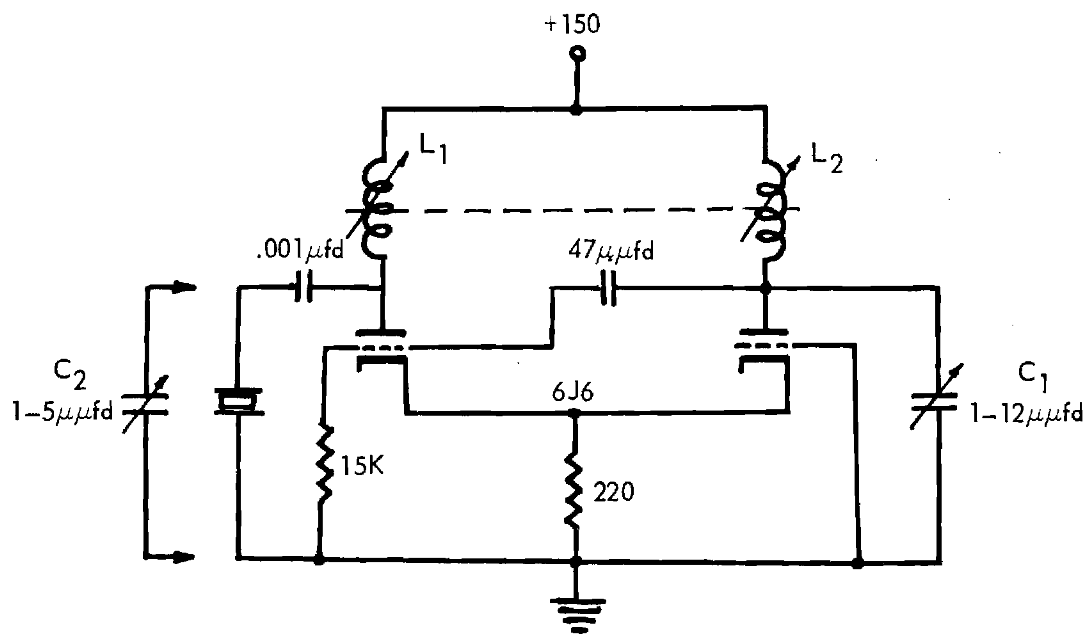

Figure 18. Plate Degenerative Oscillator.

the cathode follower gain below the value necessary to maintain oscillations. At or near the crystal series resonant frequency the cathode follower plate is effectively grounded through the relatively low crystal equivalent resistance. This degenerative action on the plate impedance causes an increase in the cathode follower gain and allows oscillations to take place. By padding the plate circuit of the grounded grid stage with a capacitor, C_1 approximately equal to C_o, satisfactory tracking may be obtained with L_1 and L_2 ganged. The tracking of the two resonant circuits should not be critical, since C_o does not have to be exactly antiresonated to provide a cathode follower plate load that is sufficiently high to reduce the loop gain below unity and prevent oscillations.

An experimental breadboard model using two ganged, shorted lines of a Mallory UHF Inductuner for L_1 and L_2 was constructed. Satisfactory operation was obtained over the entire tuning range of 160 to 280 mc/sec with substitution resistors in excess of 150 ohms and with a simulated C_o of 13 mmfd. However, the two resonant circuits did not track as expected over the entire frequency range. Slightly different settings of C_1 were required to prevent oscillations due to C_o at the high and low ends of the frequency band. This effect appears to be partially due to the unsymmetrical construction of the unit. The variable capacitor simulating C_o was mounted on a HC-6/U base and plugged into the crystal socket while C_1 was soldered directly into the circuit. The resulting difference in lead length is capable of causing the effective capacity of the mounted capacitor to vary with frequency at a rate considerably different from that of C_1.

The band of frequencies covered by the shorted lines of the inductuner are shifted according to the C_o and C_1 shunt capacity. Consequently, the frequency coverage is a function of C_o and varies from crystal to crystal. It is conceivable that the frequency range can be fixed by adding a variable capacitor C_2 across C_o such that $C_o + C_2$ can always be set equal to a fixed value of C_1.

Initial checks of the oscillator using crystal units were encouraging. For instance, crystal Z-46 operated satisfactorily at the 7th and 9th overtone frequencies of 168 and 216 mc/sec. The equivalent resistance at 168 mc/sec appeared to be approximately 130 ohms. Present plans call for construction of a more permanent model of this circuit in order that more concise crystal checks can be made.

D. Power Measurements

For the initial measurements, the voltage across the crystal has been measured to indicate the power dissipation. The voltmeter cannot remain across the crystal while impedance measurements are being made and thus cannot be used as a power level monitor. The accuracy of power calculations on the basis of voltage is also questionable because of field disturbances caused by the voltmeter probe. A more basic and reliable power measuring system is desirable. For this reason the use of directional couplers and other devices is being considered. By the use of a dual directional coupler, both transmitted and reflected power may be measured and the dissipated power thus calculated. Because of the low VSWR of such devices, they may be left in the circuit while impedance measurements are being made. The literature indicates that accuracies of better than 5 per cent can be obtained at power levels above one milliwatt. This system appears to be particularly well suited for use with the crystal measurement standard as well as with the proposed coaxial bridge system. Two dual directional couplers are presently on order and an experimental investigation of this system will be initiated on their arrival.

Measurement of the crystal power dissipation in both the standard and routine systems can be simplified if one terminal of the crystal unit is grounded. For instance if neither terminal is grounded, the directional coupler method requires measurement of the incident and reflected power at both the input and output of the crystal unit. This would require two directional couplers. Only one unit is required for a grounded crystal configuration since it is necessary to measure only the incident and reflected power at the input. In general, all measurements on a four-terminal or ungrounded crystal are more difficult than those of a two-terminal or grounded crystal.

Another power measuring system under consideration is the substitution calorimetric system. This method uses two identical calorimetric bodies within one of which is placed the object whose power dissipation is to be measured. The temperature difference of the calorimetric bodies is then recorded as a function of time. The system automatically compensates for ambient temperature variations. Accuracies of better than one per cent are claimed at frequencies around 300 mc.[4] This system is well suited to measurements in the milliwatt range. It also has the advantage that it can be calibrated at direct current for greater precision.

VI. CONCLUSIONS

Practical VHF Rheostats can be constructed which exhibit phase angles of less than $\pm 11^{\circ}$ over a resistance range of 30 to 200 ohms at frequencies up to 300 mc/sec. These units provide satisfactory substitution and bridge-balancing elements for use in active crystal parameter measuring systems.

A crystal measurement standard using available commercial equipment has enabled preliminary measurements to be made on a number of crystals. Although general agreement was obtained for measurements made with different commercial bridges, definite discrepancies were noticed. The laboratory setup has emphasized the need for a more stable signal source, an improved detector system and accurately calibrated instruments, as well as the necessity of further study of the effect of line lengths, crystal power variation and measurement techniques.

A hybrid coaxial bridge has been constructed which promises to extend the upper frequency limit of the active Crystal Parameter Bridge system. Arrival of the HP-764D directional couplers used in this bridge will permit experimental checks to be made on the usefulness of this device.

Construction of breadboard models of several oscillator configurations suitable for use in active substitution or bridge measurements systems indicates probable operation up to 300 mc/sec. One circuit, a Degenerative Plate Oscillator, appears to be particularly well-suited for a bridge measurement system in that it simply compensates for the crystal holder capacity and allows the crystal unit to be grounded.

A directional coupler and a substitution colorimetric power measuring system are being considered as possible methods of measuring crystal dissipation.

Although promising, definite conclusions as to the usefulness of these methods must await the receipt of the directional couplers and the results of the experimental measurements.

VII. PROGRAM FOR NEXT QUARTER

Work during the next quarter will be a continuation of that reported in the preceding pages, with emphasis on the following objectives:

1. Construction and test of a coaxial bridge system utilizing directional couplers,
2. Test of various "active" oscillator circuits,
3. Continued investigation of methods for measurement of crystal power dissipation,
4. Calibration of the commercial bridges for use with the "passive" systems, and
5. Construction of stable variable frequency sources using cavity, butterfly and frequency synthesizer configurations.

Respectfully submitted:

Douglas W. Robertson
Project Director

Samuel N. Witt, Jr.
Research Engineer

Approved:

J. E. Boyd, Head
Physical Sciences Division

Paul K. Calaway, Director
Engineering Experiment Station

VIII. PERSONNEL

Mr. James E. Lane, Technical Assistant, was employed by this project on a part-time basis and is currently devoting one-fourth time to project work. Mr. Lane has previously been connected with the station as a technician on various other projects. He has had four years experience in military electronic maintenance and is at present a senior student in Industrial Management at Georgia Tech.

This project is under the direction of Mr. Douglas W. Robertson, Research Engineer, who devotes full time to this work. Mr. Robertson is a graduate of the Georgia Institute of Technology and holds the degree of B.S. in Electrical Engineering. He had approximately nine years of experience in the field of electronic circuitry prior to employment by the Engineering Experiment Station on a full-time basis in January 1951.

Mr. Thomas R. Scott, Jr., Assistant Research Engineer, was employed by this project on a full-time basis. He served 3-1/2 years as an Aviation Electronics Technician in the United States Navy and now holds the degree of M.S. in Electrical Engineering from the Georgia Institute of Technology. Mr. Scott has been employed by the Engineering Experiment Station since March 1952 and has had considerable experience with electronics in the field of underwater sound and VHF techniques.

Mr. Samuel N. Witt, Jr., Research Engineer, was employed by this project on a half-time basis. Mr. Witt, who holds the degree of Master of Science in Electrical Engineering from Georgia Tech, is currently pursuing studies toward a Doctor of Philosophy degree in that field. He served one year as an electronics instructor in the U. S. Navy and one year as electrical engineering instructor at Tennessee Polytechnic Institute and has been associated with this station on several projects since 1951.

IX. REFERENCES

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2. Guttwein, G.K., Extension of the Upper Frequency Limit of Crystal Impedance Meters. Engineering Report No. E-1170, Signal Corps Engineering Laboratories, Fort Monmouth, N.J., January 1956.

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4. Schrack, R.A., "Radio-Frequency Power Measurements," National Bureau of Standards, Circular 536.

ENGINEERING EXPERIMENT STATION
of the Georgia Institute of Technology
Atlanta, Georgia

PROGRESS REPORT NO. 2

PROJECT NO. A-271

INVESTIGATION OF METHODS FOR MEASURING THE EQUIVALENT ELECTRICAL PARAMETERS OF QUARTZ CRYSTALS

By

DOUGLAS W. ROBERTSON, S.N. WITT, Jr. and WILLIAM R. FREE

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CONTRACT NO. DA-36-039-sc-71191

DEPARTMENT OF THE ARMY PROJECT NO. 3-24-02-072
SIGNAL CORPS PROJECT NO. 867B

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16 JULY TO 15 OCTOBER 1956

PLACED BY THE U. S. ARMY
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FORT MONMOUTH, NEW JERSEY

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I. PURPOSE

The purpose of this project is threefold:

1. To study and investigate methods and techniques for measuring the equivalent electrical parameters of quartz crystal units in the frequency range of 150 to 300 mc/s, including:

   (a) A means for directly measuring the power drive of a crystal unit,

   (b) A simple and practical means of cancelling the capacitance of the crystal unit, C_o, at the test frequency, and

   (c) A means of measuring the effective resistance of the crystal unit at the series resonant condition.

2. To accumulate data from the investigations of 1. above, with a view of utilizing the information for the development of a practical test method for the frequency range 150 to 300 mc/s which will make it possible to:

   (a) Subject the crystal to any selected drive level between the limits of 0.2 and 4.0 milliwatts,

   (b) Measure crystal resistance values between the limits of 20 and 200 ohms,

   (c) Attain an accuracy of resistance measurement of $\pm$ 5 ohms or $\pm$ 10 per cent, whichever is greater, and

   (d) Attain an accuracy of resonant frequency determination within $\pm$ 0.001 per cent of the series resonant frequency of the crystal unit.

3. To study and investigate means for establishing a laboratory measuring technique to be used as a standard for measuring the equivalent electrical parameters of quartz crystal units in the frequency range of 100 to 300 mc/sec.

II. ABSTRACT

Work on the crystal measurements standard has continued at a reduced rate during this report period while awaiting the arrival of various instruments and technical information. Crystal measurements over a period of 5 months have been compared to determine the reliability and accuracy of the previously reported measurement setup. Initial attempts have been made to measure power in the standards system by the application of directional couplers. Work has continued on the development of a more sensitive detector system for use with standard impedance bridges.

Investigations have been made to determine the optimum calibration accuracy of instruments to be used in the standard measurement setup. Results from these preliminary investigations indicate that calibration accuracies better than 1 per cent are impractical.

Two experimental crystal oscillators, the Plate Degenerative Oscillator and a capacitance bridge oscillator, appear suitable for use as driving sources for the coaxial crystal parameter bridge being developed. Both of these oscillators allow one terminal of the crystal unit to be grounded and provide for cancellation of the crystal holder capacity over a wide frequency range. Experimental models of each have been successfully operated with various crystals at frequencies up to and above 300 mc/sec.

A calorimetric system utilizing a thermistor bridge is being investigated as a possible means of measuring the power dissipation in VHF crystals. Indications are that this system offers sufficient sensitivity and adequate ambient temperature compensation when small bead thermistors are used in adjacent legs of a wheatstone bridge. The system makes possible the measurement

of crystal power dissipation without any electrical connection to the crystal parameter bridge.

The impedance-transforming properties resulting from the electrical length of the commercial directional couplers makes them unsatisfactory for use in the proposed coaxial crystal parameter bridge. A compact self-contained bridge using short, single directional couplers has been designed to overcome this difficulty. Directional couplers rather than simple capacitive or inductive probes have been retained as the sampling device because of their ability to give a relative measure of the crystal power.

III. EXPERIMENTAL WORK AND CIRCUIT STUDIES

A. Crystal Measurement Standard

1. Introduction

Work on the crystal measurements standard has continued at a reduced rate during this report period while awaiting the arrival of various instruments and technical information. Some additional experimental data have been obtained on selected crystals for comparison with previously reported data. Directional couplers have been received and evaluated as to their effects on measurements. Crystal measurements over a period of 5 months have been compared to determine the reliability and accuracy of the previously reported measurement setup.

Initial attempts have been made to measure power in the standards system by the application of directional couplers. Sufficiently accurate and sensitive power measurements have not yet been realized.

Work has continued on the development of a more sensitive detector system for use with standard impedance bridges. It has been observed that lack of sufficient detector sensitivity is one of the principal sources of error in accurately determining the resonant resistance and frequency of crystals.

Satisfactory calibration of instruments has not yet been realized due principally to limitations in the "state of the art." It is presently believed that impedance calibration will be limited to not better than $\pm$ 1 per cent unless a very costly calibration service is engaged.

2. Experimental Data

Several additional circle diagrams have been obtained on crystals number 2-W and 3-W on which data have been previously reported. The setup used is shown in Figure 1 and is identical to that previously reported except that directional couplers have been added for some of the runs. A summary of results showing the resonant frequency and conductance is presented in Table I. Omitted from this table are runs which involved purposeful misadjustment and runs which were obviously greatly in error even though the source of error was unexplained (some difficulties were experienced because of leakage and poor connections in the General Radio connectors used for assembling the system).

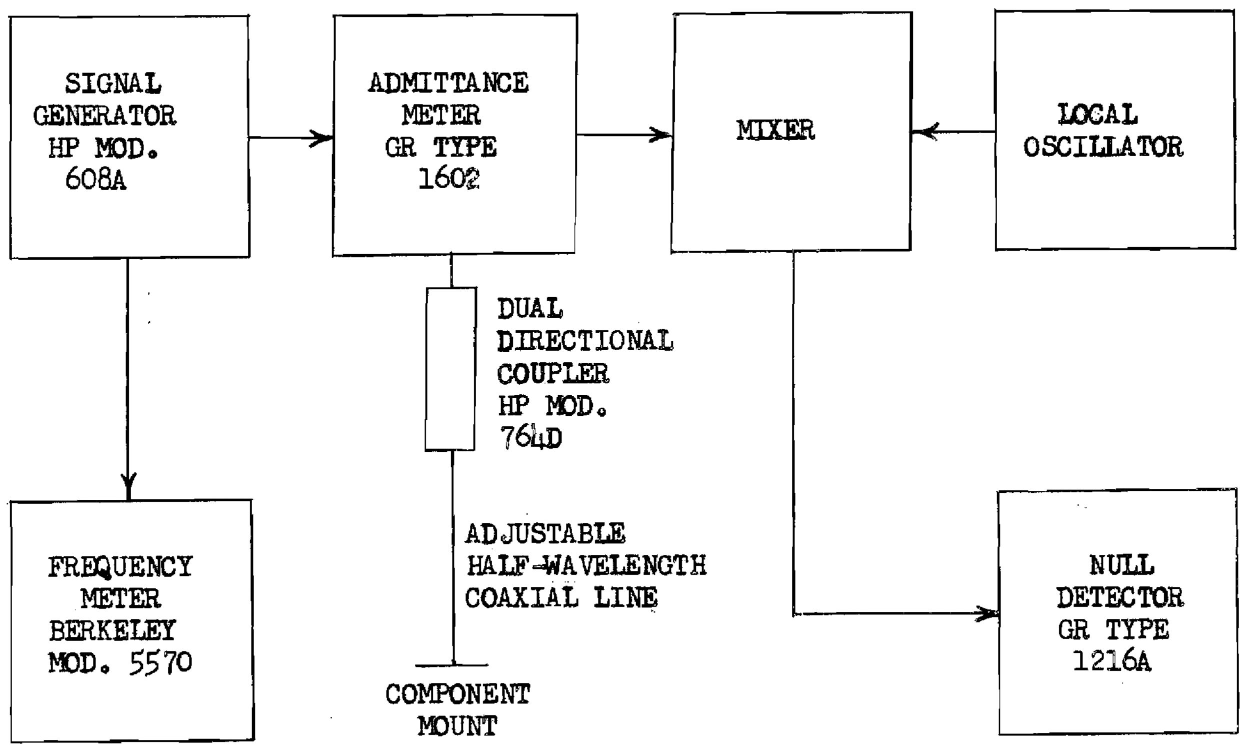


Figure 1. Block Diagram of the Laboratory Standard Measurement Setup.

TABLE I

SUMMARY OF MEASUREMENTS ON CRYSTALS 2-W AND 3-W

Crystal No.	Run No.*	Date	G (mhos)	f (mc)	Notes**
2-W	1	4-26-56	0.0248	125.11058	
	2	4-26-56	0.0245	.11065	
	4	5-2-56	0.0255	.11081	
	23	5-22-56	0.0260	.11065	HP
	33	10-2-56	0.0265	.11138	DC
	34	10-2-56	0.0270	.11155	DC
	35	10-2-56	0.0260	.11183	
	36	10-2-56	0.0260	.11099	DC
	A	11-14-55	0.025	.11200	
	B	11-14-55	0.025	.11170	
	C	11-14-55	0.025	.11160	
	D	12-5-55	0.0262	.11155	
	E	12-5-55	0.0243	.11132	
3-W	6	5-4-56	0.036	124.78693	
	7	5-7-56	0.037	.78695	
	24	5-25-56	0.037	.78632	HP
	37	10-9-56	0.0325	.78883	DC
	39	10-12-56	0.034	.78720	DC
	40	10-15-56	0.032	.78772	
	41	10-16-56	0.031	.78892	
	A	11-14-55	0.030	.78711	
	B	11-14-55	0.029	.78610	
	C	11-14-55	0.030	.78670	
	D	12-5-55	0.027	.78670	
	E	12-5-55	0.027	.78743	

* Run No. A--Sig. Corps w/TS 683
B--Sig. Corps w/FCB VHF-CI Meter
C--Sig. Corps w/GIT CI Meter
D--Ga. Tech w/TS 683 and Bridge
E--Ga. Tech w/GIT CI Meter and Bridge
All Others-w/Crystal Measurements Standard

** Notes: HP--Using HP-VHF Bridge (All other runs--GR Admittance Meter)
DC--Using Dual Directional Coupler in Half-Wavelength Line.

Also included in the table are data measured at the Signal Corps Engineering Laboratory and at Georgia Tech using CI meters. Table II shows a summary of maximum differences obtained using the laboratory standard. It should be observed that these data were obtained under non-temperature controlled conditions and with possible power level variations as great as 100 per cent. In addition, some of the runs contained a directional coupler in the half-wave line and some of the runs were made using the HP-VHF Bridge rather than the admittance meter. The purpose of adding the directional coupler was to determine its effect on the impedance and frequency measurements. The data presented in Table I indicated that the effect of the couplers is negligible compared to other sources of error. Thus the directional couplers provide an isolated means of measuring the true power dissipated in the crystals.

TABLE II

MAXIMUM DIFFERENCE READINGS FOR CRYSTALS 2-W AND 3-W

Crystal Number	Max. Diff. in G (%)	Max. Diff. in f (ppm)
2-W	± 5	± 7
3-W	±10	±10

The errors indicated in Table II are attributed to four principle sources: (1) the inability to set and maintain the proper frequency with the HP608A Signal Generator as the signal source, (2) the inability to obtain a sufficiently sensitive null indication with the equipment shown in Figure 1 at the power level involved, (3) the inability to measure power accurately and (4) changes in the crystals over the period of time between measurements.

It should be observed that the numbers in Table II in no way indicate the absolute accuracy of the system but rather indicate the inconsistencies in the system over a period of 5 months. It is obvious that the inconsistencies in the system must be reduced below the required accuracy limits. Indications are that improvements in signal source stability and detector system sensitivity will greatly reduce these inconsistencies.

Since the previous report, the system shown in Figure 1 has been improved by the addition of clip-locks on all GR connectors and the use of a GR 874-Z Stand for mechanically supporting the half-wavelength line and component mount. It has also been observed that a mechanical vernier is needed for the precise adjustment of the half-wavelength line. This feature has not yet been added.

No further tests have been made with the HP-VHF bridge because of the lack of a sufficiently sensitive detector.

3. Stable Signal Generators

Work has continued on the development of a laboratory-constructed signal source. The system shown in Figure 13 of Progress Report No. 1 was chosen for further development. This work was delayed, however, by the need for a stable, crystal controlled VHF oscillator capable of supplying appreciable power output at frequencies as high as 255 mc. It appears now that one of the oscillators described in Chapter III, section B, of this report can be adapted to this application.

Less effort was placed on this phase of the work because of the promised delivery of a Marconi Type 1066A Signal Generator which is believed to be sufficiently stable to meet the immediate needs of the project. This signal generator was placed on order August 8, 1956 with promised delivery 70-90 days after receipt of the order by the manufacturer. Thus, delivery is expected during the month of November.

Qualified personnel have not yet been available to investigate the applications of cavity controlled oscillators as stable signal sources in this frequency range.

4. Power Measurements

As indicated in Figure 1, directional couplers have been inserted into the half-wavelength line for the purpose of measuring transmitted and reflected power. It has been determined that the resulting mismatch is sufficiently small so as to not have appreciable effect on the presently obtainable accuracy. Since the attenuation of the directional couplers is 20 db, it is necessary that voltages from 10 to 100 mv be measurable with inaccuracies not exceeding 5 per cent. Considerably better accuracies are desirable but apparently not obtainable with presently available commercial equipment. Various sensitive voltmeters have been investigated by the project but none has yet shown reliable accuracy even as good as 5 per cent. Loans of other voltmeters have been promised by various manufacturers' representatives as an aid in selection of meters suitable for this application.

An absolute power reference has not yet been established; however, plans have been formulated for the use of accurate higher level power measuring instruments for the calibration of sensitive instruments having lesser absolute accuracies. By this means it will be possible to employ a receiver which has been precalibrated to the required accuracy for measuring the output from the directional couplers.

5. Detector Systems

As mentioned previously, the detector system indicated in Figure 1 is not sufficiently sensitive to obtain highly accurate null indications at the power levels involved. Thus, investigations of other detector systems have been made. A tuning unit (TU-17) for the AN/APR-4 receiver covering the range from 75 to 300 mc has been purchased by Georgia Tech for use by the project. The sensitivity of this receiver has been found to be considerably lower than was originally anticipated. Its sensitivity is compared to that of the system using the GR I-F Amplifier in Figure 2 (the lack of sensitivity near 170 mc for the i-f amplifier system is probably caused by greatly decreased local oscillator output). Other receivers having sufficient sensitivity, as

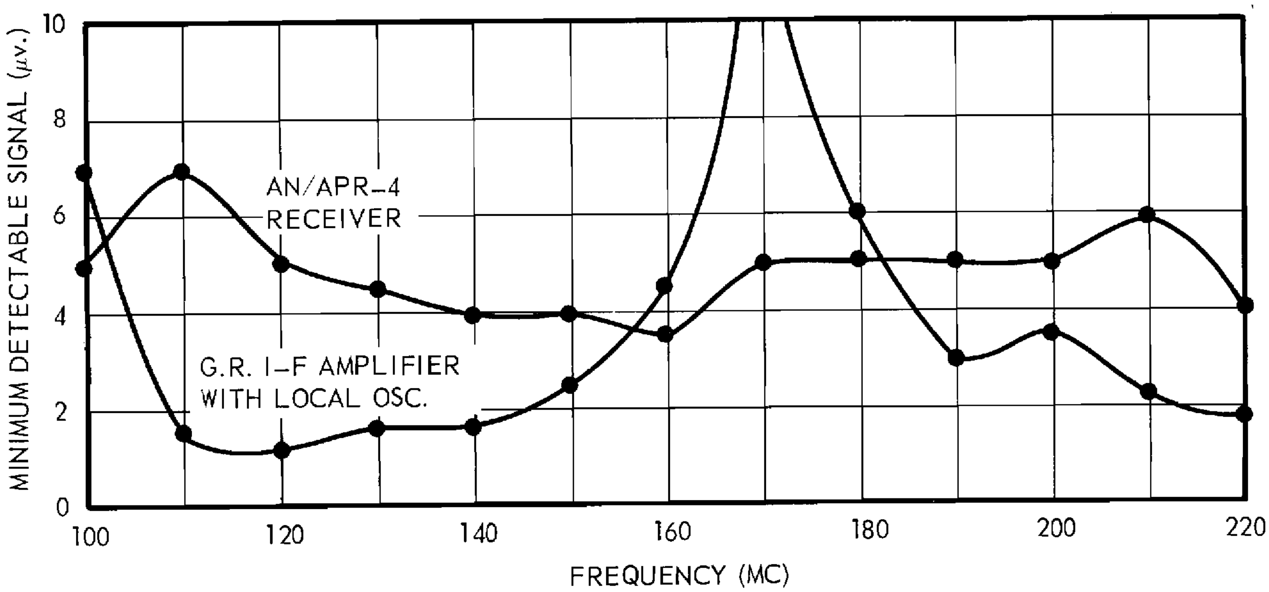


Figure 2. Sensitivity of Two Null Detector Systems

stated in Progress Report No. 1, are beyond the economic reach of the project. However, a modification of the AN/APR-4 receiver is being considered which may provide adequate sensitivity.

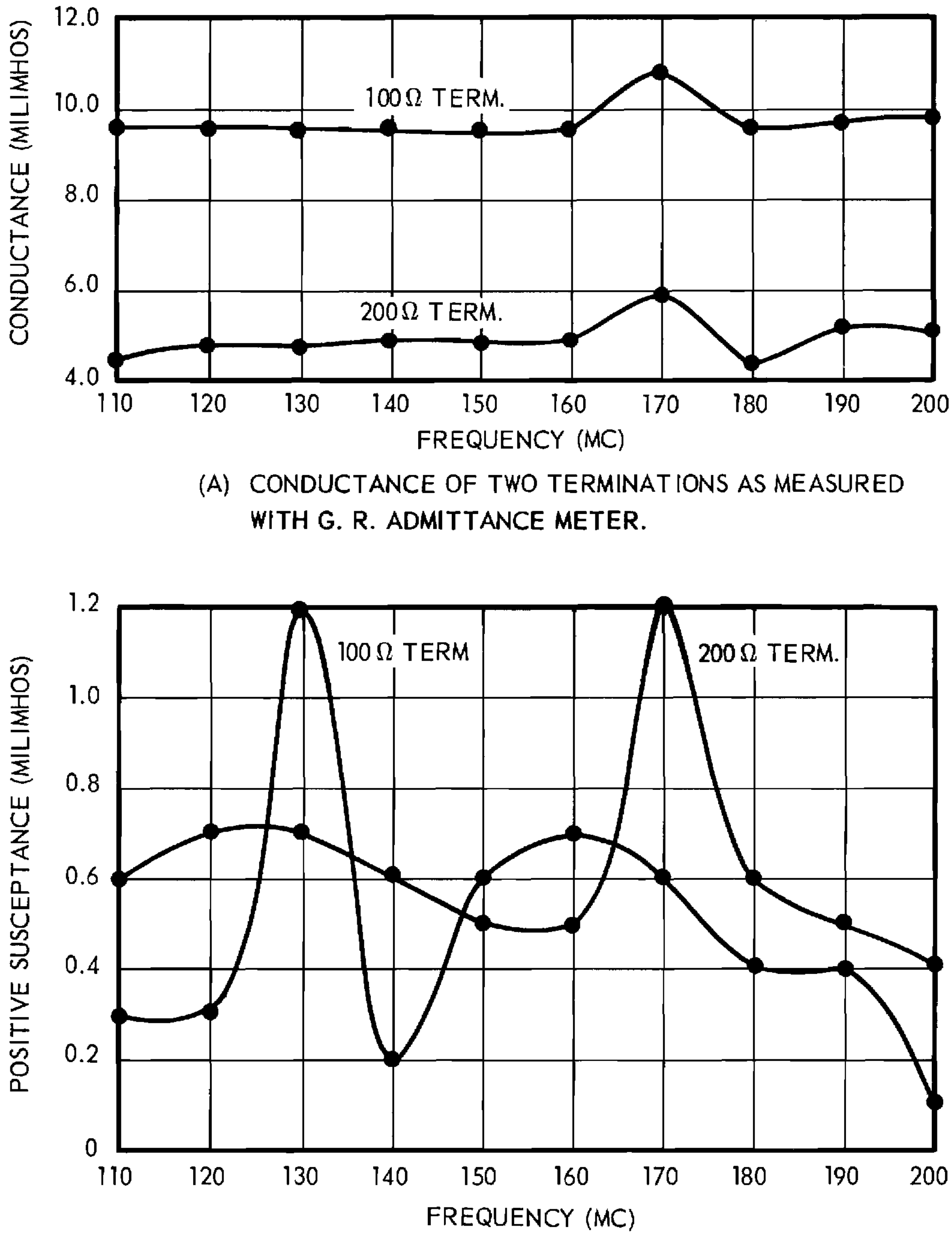
6. Impedance Calibrations

Calibration of instruments is practical only to the accuracy as limited by their long term electrical and mechanical stability. For example, it would be pointless to calibrate a bridge to an accuracy of 0.1 per cent if random variations in the instrument reading amounted to 1 per cent. Thus, attempts have been made to determine the optimum calibration accuracy of instruments to be used in the standard measurement setup. Although this investigation is not complete, it appears that it would not be practical to calibrate any of the bridges under consideration to accuracies better than 1 per cent unless a simple recalibration procedure were possible in the project laboratory.

Communications with the General Radio Company and with the National Bureau of Standards indicate that calibration of the General Radio Type 1602-B Admittance Meter and Type 874 terminations to their maximum capabilities could require up to 6 or more man-months of time at a calibration laboratory. The General Radio Company indicates that calibration to 0.1 per cent would be impractical (even if the laboratory facilities were available) because of time and temperature drifts of the components themselves. The National Bureau of Standards indicates that they cannot presently attempt calibration of any type except for "a legal decision or execution of a vital defense contract." They state however, that such facilities should be regularly available within about one and one-half years.

Thus, it appears that an accuracy of the order of 1 per cent (the standard calibration accuracy of the General Radio Type 874 terminations) must be accepted for the present. Even this accuracy is not presently attainable because of other cumulative errors. For example, since the General Radio Admittance Meter is calibrated only to an order of 3 per cent, it is first necessary to calibrate this instrument more accurately using the terminations. This, of course, cannot be accomplished without some loss in accuracy. Additional error is introduced by signal source instability, lack of sufficient null detection sensitivity at low power levels and limited scale resolution on the instrument. To determine the Admittance Meter calibration error, the impedances of two terminations were measured over a range of frequencies using a half-wavelength line. The results of these measurements are shown in Figure 3. When studying this figure it must be remembered that the terminations are calibrated only to 1 per cent and that errors may also be introduced in setting up the half-wavelength line. In addition, as may be seen from Figure 2, the sensitivity of the detector system using the i-f amplifier is poor at 170 mc, causing increased errors in admittance measurements at this frequency. The increased reactive component of the 100-ohm termination at 130 mc is unexplained.

Considering all of the factors involved, the forseeable accuracy of the standard crystal measurement setup can only approach 1 per cent. The present accuracy is much poorer than this due to undetermined sources of inconsistencies as indicated by the previously presented data on crystals number 2-W and 3-W. Some of the variations recorded for these crystals may be attributed to temperature of operation, power level variations and aging over the 5-month period.



(A) CONDUCTANCE OF TWO TERMINATIONS AS MEASURED WITH G. R. ADMITTANCE METER.

(B) SUSCEPTANCE OF TWO TERMINATIONS AS MEASURED WITH G. R. ADMITTANCE METER.

Figure 3. Impedance Measurement of Standard Terminations.

A study of all of the data gathered to date indicate that the overall system is presently accurate to better than 5 per cent even when using the HP Model 608A Signal Generator as the signal source.

No further attempts will be made to achieve more accurate calibration of equipment until the Marconi 1066A Signal Generator is obtained, a better null detector is developed and a more accurate power measuring system is realized.

B. Experimental Oscillators

1. Introduction

Additional experimental tests were made on the crystal oscillators described in Progress Report No. 1 and several other configurations were investigated. Of those tested, two appeared to exhibit qualities worthy of continued investigation. Both of these configurations allow one terminal of the crystal unit to be grounded and also provide cancellation over a wide frequency range of the crystal holder capacity C_o.

The first and most promising, the Plate Degenerative Oscillator, utilizes a cathode-coupled amplifier in which an inductive cathode follower plate load is incorporated to antiresonate with C_o. The second utilizes a grounded grid amplifier and balances out the effects of C_o with a transformer-coupled capacitive bridge arrangement. Experimental models of both oscillators have been successfully operated with various crystals at frequencies up to and above 300 mc/sec. These two circuits are being considered as driving sources for the coaxial crystal parameter bridge presently being developed.

2. Plate Degenerative Oscillator

The Plate Degenerative Oscillator shown schematically in Figure 4 may be considered as a modified cathode-coupled or differential amplifier in which the output at the plate of the grounded grid stage is fed back as an input to the grid of the cathode follower. If a loop gain of greater than one exists and proper phase relations are maintained, oscillations will take place.

A mathematical analysis of the oscillator in the vicinity of 300 mc/sec is not practical because of the inability to adequately describe or include the stray reactance and transit time effects at such frequencies. However, a low frequency analysis does serve to illustrate a possible manner of obtaining crystal controlled oscillations. The inductance L_1 is tuned to antiresonate

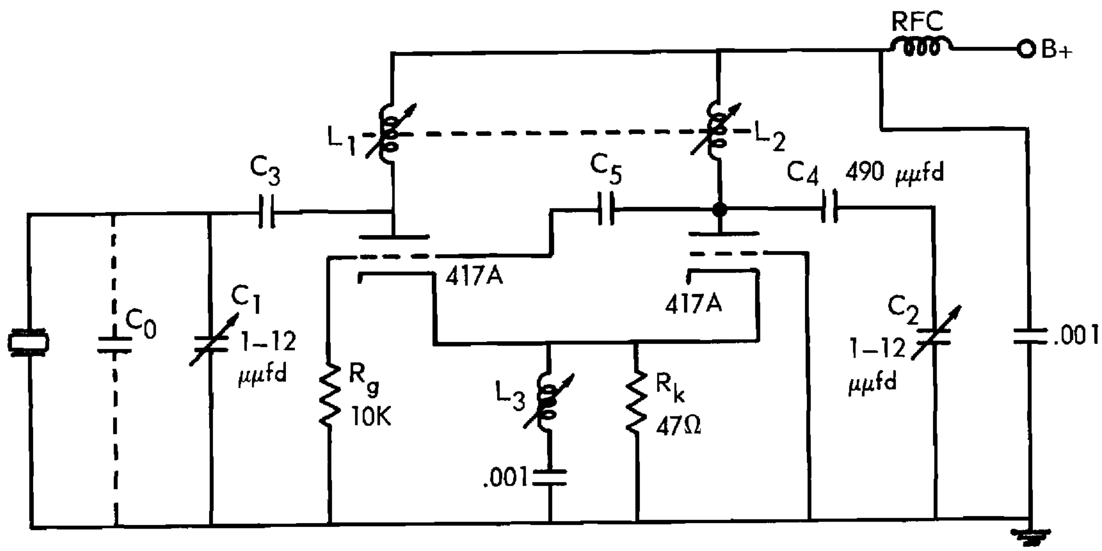


Figure 4. Plate Degenerative Oscillator

the net capacity presented by C_0, C_1, C_3 and the circuit strays. The resulting antiresonant resistance of this tuned circuit appears as the cathode follower plate load R_{L_1}. Similarly the inductance L_2 is tuned to antiresonate, at the same frequency, the net capacity presented by C_4, C_2 and the circuit strays; and the tuned circuit appears as a plate load R_{L_2} for the grounded grid stage. C_1 and C_2 allow the net capacities of the two tuned circuits to be set equal, so that satisfactory tracking is obtained with ganged inductances. At the desired frequency of operation the crystal appears as its equivalent series resistance R_1. Since R_1 is considerably smaller than the antiresonant resistance of the tuned circuit, the cathode follower plate load is reduced to approximately R_1. At the crystal frequency the grounded grid plate load remains unchanged. Normally $R_g \ll R_{L_2}$ and $R_{L_2} \doteq R_{L_2} R_g/(R_{L_2} + R_g)$. Since $C_o + C_1$ is adjusted to equal C_2 and $L_1 = L_2$, then the antiresonant resistances and, therefore, R_{L_1} and R_{L_2} are approximately equal at frequencies other than that of crystal resonance. The circuit may be broken for analysis at the grid of the cathode follower and appears as the equivalent circuit of Figure 5. In terms of the loop gain, the circuit, to be capable of oscillations at the crystal frequency, must exhibit a gain e_{o_2}/e_1 that is at least unity when the

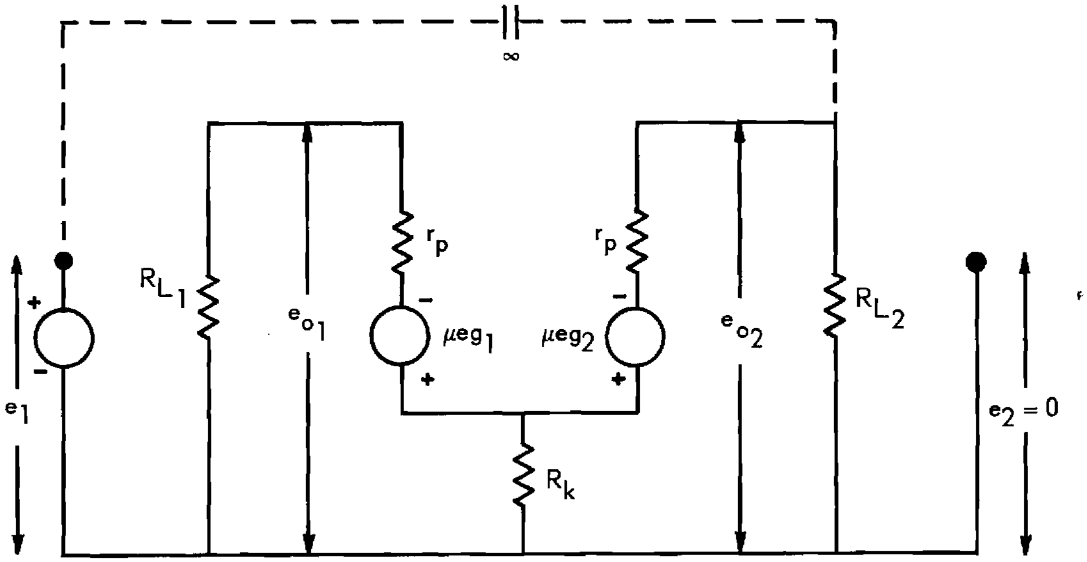


Figure 5. Equivalent Circuit of Plate Degenerative Oscillator.

circuit is tuned to the crystal series resonant frequency. In addition, the gain must be less than unity when tuned to other frequencies. If the tubes are assumed to be identical, then $\mu_1 = \mu_2 = \mu$ and $r_{p_1} = r_{p_2} = r_p$. The expression for the gain of the amplifier may be written as[1]

$$\frac{e_{o_2}}{e_1} = \frac{\mu R_{L_2} R_k}{\dfrac{(R_{L_1} + r_p)(R_{L_2} + r_p)}{\mu + 1} + R_k(R_{L_1} + R_{L_2} + 2r_p)} \quad . \qquad (1)$$

The two conditions of interest are:

1. when the tank circuits are tuned to the crystal series resonant frequency and $R_{L_1} \doteq R_1$ and

2. when the tuned circuits are tuned to a frequency other than that of the crystal and $R_{L_1} = R_{L_2}$.

Substitution of reasonable circuit parameters of $R_k = 50$ ohms, $R_{L_2} = 2000$ ohms and $R_1 = 100$ ohms and the parameters for a WE417A tube of $\mu = 40$ and $r_p = 2000$ ohms in equation 1 allows the gain to be obtained for the two conditions. A gain of approximately 10 is obtained for condition (1) and approximately 5 for condition (2).

From this analysis it is evident that the amplifier gain at the crystal resonant frequency is about twice that obtained at other frequencies. It should be pointed out that the gain figures obtained are the low frequency gains which would be considerably reduced at 300 mc. It therefore appears possible to obtain a gain greater than unity at the crystal frequency and less

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[1] Seely, Samuel, Electron Tube Circuits. McGraw Hill, New York, 1950, 113-117.

than unity at other frequencies. This would allow crystal controlled oscillations to occur and the circuit to operate as described in Progress Report No. 1. However, from a practical viewpoint a gain ratio of two appears to be too small to be consistent with the reliable operation obtained with several experimental models. Evidently, some additional factor is present which either aids the described action or is itself the primary controlling factor. Such a factor may be the signal coupled through the interelectrode and stray reactance from the cathode follower plate to its grid. The voltage at the plate of the cathode follower may be expressed as[1]

$$e_{o_1} = \frac{-\mu R_{L_1}\left(\frac{R_{L_2}+r_p}{\mu+1}+R_k\right)e_1}{\frac{(R_{L_1}+r_p)(R_{L_2}+r_p)}{\mu+1}+R_k(R_{L_2}+R_{L_2}+2r_p)} \quad . \qquad (2)$$

Substitution of the circuit parameters in this equation allows the relative cathode follower plate voltage, e_{o_1}, to be obtained for each of the two conditions. Since this voltage is approximately 180° out-of-phase with that on the grid, any portion coupled to the grid would constitute negative feedback and would tend to prevent oscillations from occurring. The voltage at the crystal series resonant frequency as obtained by equation 2 is found to be approximately one-tenth of that obtained at other frequencies. Because of this decreased voltage it is evident that the negative feedback through this path would be considerably reduced at the crystal frequency. The combination of this effect and the change in gain as obtained from equation 1 is capable of causing a net change in oscillator loop gain of greater than two-to one.

Although the phase relationships that occur at or near frequencies of 300 mc have not been included, the above analysis does serve to illustrate the probable method by which crystal controlled oscillations are obtained.

Progress Report No. 1 mentioned the difficulties encountered in obtaining satisfactory tracking of the breadboard model over the frequency range of 150 to 300 mc. Consequently, three models, each covering a portion of the entire range, were constructed. The circuits and physical arrangements of the three models are similar although minor differences, such as the value of L_3, do occur. These differences serve to optimize preformance over the frequency range covered by that particular unit.

As would be expected, the highest frequency model is the most critical. However, consistent operation has been obtained in this unit with several crystals at frequencies up to and including 325 mc. In particular, crystal units 2-W, 3-W and D6 operated satisfactorily in the high frequency unit at the 11th and 13th overtone frequencies of 275 and 325 mc. No adjustment other than the initial setting of C_2 to balance $C_o + C_1$ for each crystal was necessary in order to obtain crystal controlled operation over the tuning range of approximately 260 to 330 mc.

It should be pointed out that although crystal controlled, the oscillators will free-run if the crystal is removed. This results from the low plate impedance that occurs at the cathode follower plate when the plate inductance is no longer resonated by the crystal holder capacity.

The present models using Mallory UHF Inductuners (shorted lines) have an upper frequency limitation of approximately 350 mc when shunted with a capacity of the same order of magnitude as C_o. Since the coaxial bridge under development will present a net capacity to the inductuner of approximately twice C_o, the upper frequency limit will be reduced. However, it has been determined experimentally that this capacity can be effectively reduced by making the series blocking condensor C_3 equal to approximately twice the value of C_o without seriously affecting the operation of the oscillator as previously described. As discussed in Chapter III, section C, a suitable coaxial bridge has not been completed for use with the oscillator and no tests of the combination have been made.

3. Capacitance Bridge Oscillator

Capacitance bridge oscillators provide a method of balancing the effects of C_o by feeding an equal out-of-phase signal through a capacitor equal to C_o so as to effectively cancel the signal due to C_o. An oscillator configuration utilizing such an arrangement in a manner which allows the crystal to be grounded is shown in Figure 6. The capacitance bridge is formed by the tapped secondary of the transformer, the crystal holder capacity C_o and the bridge balancing capacitor C_v. One side of the crystal unit is grounded by taking as an output the difference voltage existing between the secondary center tap and ground. A single grounded grid amplifier furnishes sufficient gain to maintain oscillations near or at the crystal resonant frequency.

A breadboard model of this oscillator using a 2-in. hairpin loop for the primary and a 1-in. loop for the secondary satisfactorily tuned over a frequency range of approximately 200 to 300 mc. Crystal units were successfully operated at frequencies up to 307 mc. One advantage of this oscillator is that the larger capacity presented by the coaxial crystal parameter bridge is easily balanced and actually allows a slightly increased loop gain due to the lowered reactance of the capacitive arms of the bridge. Some difficulty has been experienced in reducing the cross coupling to the two halves of the transformer secondary and in obtaining convenient common ground connections. Additional experimental effort is being expended on this oscillator to determine the best physical and electrical configuration.

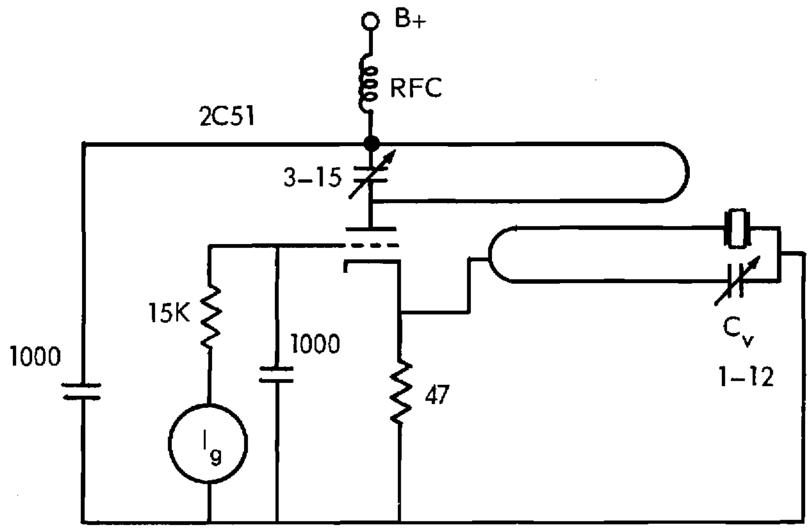

Figure 6. Capacitance Bridge Oscillator

C. Power Measurements

1. Introduction

Results from studies presently underway indicate that one side of the crystal may be grounded in the developmental test instrument. Since this configuration eliminates the difficulties due to stray reactances, it is possible that a voltmeter measurement across the crystal can be used to compute the power dissipation in VHF crystals. However, an alternate method of measuring crystal power dissipation is desirable as a comparative check of the voltage measurement and for comparison between different test instruments in which the crystal is not grounded. For this reason, considerable study has been devoted to methods of measuring low level, RF power.

The insertion of a power measuring device directly into the crystal parameter bridge could spoil the symmetry of the bridge and render any reading obtained useless. For this reason study was directed toward colorimetric systems utilizing the heat given off by a dissipating body as the power indication.

Because of the low power levels involved, a sensing element capable of detecting very small quanities of heat is required. Conventional thermocouples and barretters lack sufficient sensitivity. Thus far, results from studies indicate that the smaller bead thermistors have sufficient sensitivity for this application. Other advantages exhibited by thermistors are: (1) they can be severely overloaded without change in calibration, (2) they can be calibrated with dc power and (3) they exhibit very satisfactory stability with an indefinitely long life.

2. Experimental Data

The packaging of the crystal unit is such that a thermistor would have to be inserted into the hermetically sealed can of each crystal to obtain adequate sensitivity. This arrangement is impractical, and indicates the need for a more accessable dissipating body. Assuming that the crystal parameter bridge being developed is symmetrical and balanced (this condition is necessary for the measurement of other crystal parameters) the power dissipated in the VHF rheostat is equal to the power dissipated in the crystal. Since the VHF rheostat is much more accessible than the crystal, the thermistor can be mounted on the VHF rheostat resistive film.

The material to be used to bond the thermistor to the rheostat must exhibit both good heat conduction and good electrical insulation. At the present time, Sauereisen High Temp Cement No. P-7 is being used. This cement appears to meet the heat conduction and electrical insulation requirements, but there is some indication that the cement affects the thermistor bead in such a way that the thermistor leads become detached from the bead. However, the bond has been made successfully several times. Other materials and methods of bonding are being investigated to determine the optimum physical, thermal and electrical combination.

Another problem encountered with the thermistor as a power measuring device is the need for ambient temperature compensation. Results from preliminary studies indicate that inserting a matched thermistor in an adjacent leg of a power measuring bridge will adequately compensate for ambient termperature changes.

Figure 7 is a schematic of a thermistor bridge power measuring system presently under study. Thermistor No. T_1 is bonded to the VHF rheostat in the Crystal Parameter Bridge. Thermistor No. T_2 is bonded to a VHF rheostat in the dc reference power loop. If T_1 and T_2 are matched, any ambient temperature variations will be canceled by the two thermistors. The bridge is balanced by means of the bridge balancing potentiometer with both the VHF and dc reference power off. The VHF power to be measured is then applied to the crystal parameter bridge. The power dissipated in the VHF rheostat is given off as heat;

this heat is transferred to the thermistor causing the resistance of the thermistor to decrease, unbalancing the bridge. The bridge is rebalanced by applying dc power to the VHF rheostat in the dc reference loop. When the bridge is balanced the dc reference power is equal to the VHF power. The VHF rheostat is used in the reference loop in an attempt to assure equivalent heat transfer characteristics to both heat-sensing elements.

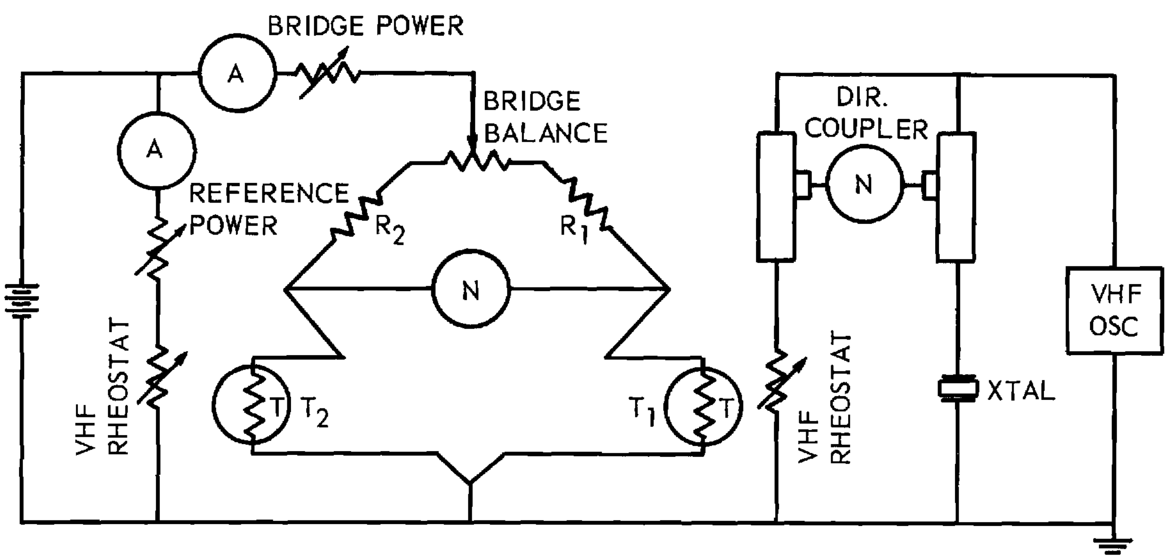

Figure 7. Thermistor Bridge Power Measuring System.

The bridge described above exhibits several desirable advantages. It makes it possible to measure the power dissipation in the crystal parameter bridge without any electrical connection. The thermistors in adjacent legs of the bridge tend to cancel out any ambient temperature variations. The dc reference power arrangement gives a direct reading of the power measured which is superior to conventional substitution methods. The system is easily calibrated with dc power.

The system as shown in Figure 7 has not been assembled because of a delay in the delivery of the desired thermistors. However, the arrangement shown in Figure 8 was used, using the less sensitive thermistors presently available, to plot the curve shown in Figure 9. This curve illustrates the magnitude of bridge unbalance-vs-dc power input to a VHF rheostat. The resolution of the balance indicator is such that 1-mm deflection can be easily detected. These results indicate that sufficient sensitivity can be realized at the power levels desired.

In the event the ambient temperature compensation and/or the dc power reference rebalancing method should prove unsatisfactory, several other systems are being considered. One such system is a self-balancing wattmeter with automatic temperature compensation.[2] This system incorporates a different approach to provide temperature compensation, zero-set, and automatic bridge rebalance. Any interaction between these three control functions is prevented by using three bias components of dissimilar types. The temperature compensation component is dc, the zero-set component is 100 kc, and the bridge unbalance component is 10 kc. However, this system is quite elaborate, and it is felt that the system presently under study, which is much simpler, is capable of giving results comparable to the self-balancing wattmeter, and at the same time, initial adjustment and calibration will be much simpler.

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[2] Eberle, E.E., "Self-Balancing Wattmeter Bridges with Automatic Temperature Compensation," Sperry Eng. Review, May-June, 1952.

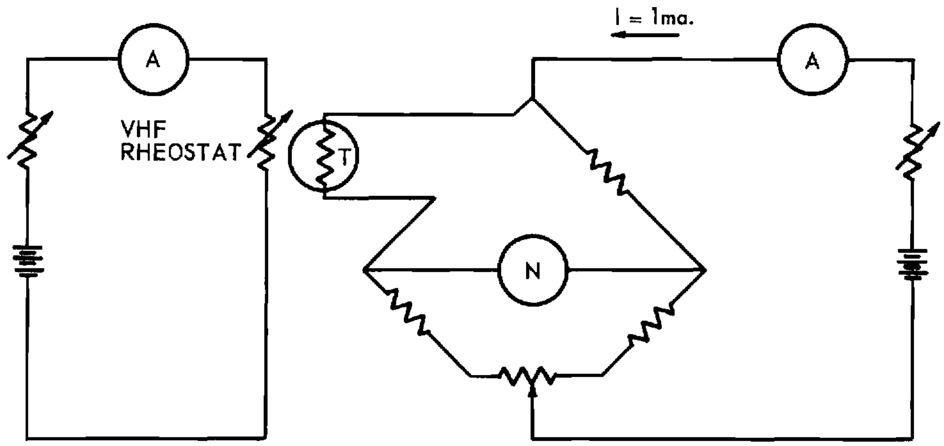

Figure 8. Experimental Thermistor Bridge.

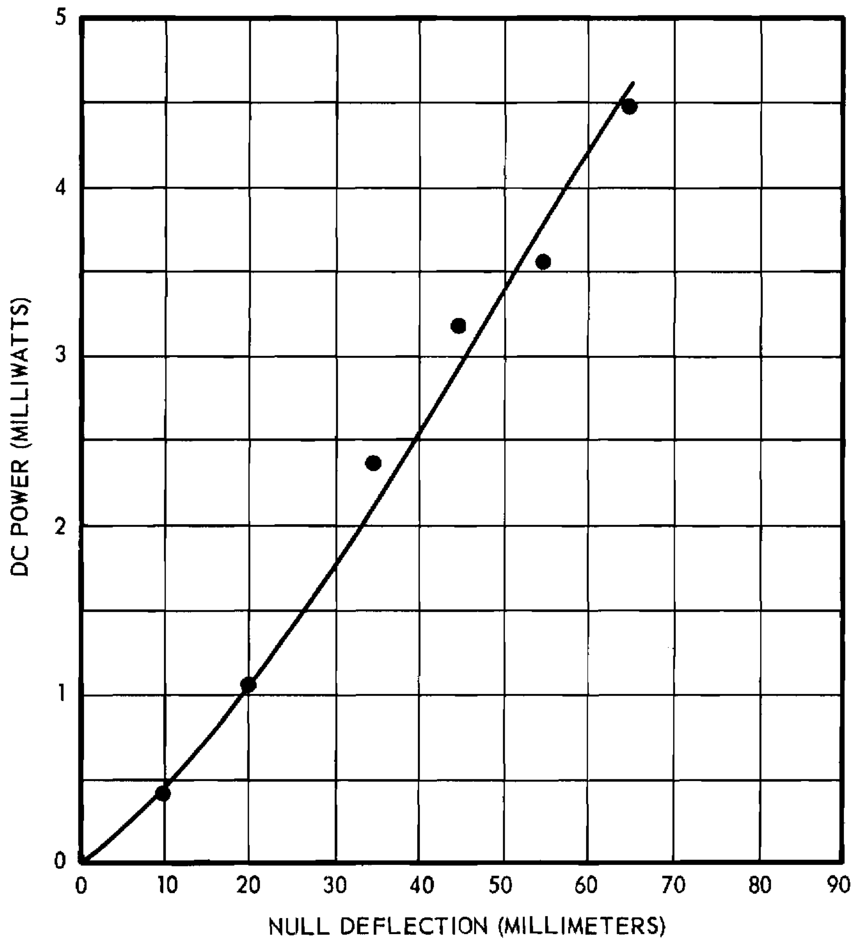

Figure 9. Bridge Unbalance vs DC Power Input.

D. Coaxial Crystal Parameter Bridge

1. Commercial Couplers

The two HP764D directional couplers necessary for completion of the experimental model of the coaxial crystal parameter bridge discussed in Progress Report No. 1 were received. However, because of their physical length the couplers were found to be unsatisfactory for use in the bridge. The 10-in. length of the transmission path through the coupler causes impedance transformations to occur throughout the 150- to 300-mc frequency range. In particular, the coupler appears as a quarter-wavelength line at 300 mc and produces an impedance inversion. In addition, the two couplers, acting in series within the bridge loop, approach a quater-wavelength at 150 mc and cause difficulties in adjusting the VHF rheostat and C_o balancing capacitor for a correct null indication. In the bridge system being developed, the oscillator is connected through the two directional couplers to the grounded crystal and VHF rheostat which in effect appear as coupler terminations. Since the oscillator is controlled by the unique impedance and phase relationships of the crystal near resonance, the impedance transformations produced by the 10-in. fixed length of the couplers cannot be tolerated.

Adjustable lines could be used with the couplers by setting the total transmission path at a given frequency at a half-wavelength. Such an arrangement would, however, require readjustment of the lines for each crystal frequency. This frequency sensitive adjustment, in addition to the oscillator tuning, would increase the complexity of the device beyond that desired for a routine test instrument.

Other commercial directional couplers were investigated in regard to their length but none were located whose length would not cause serious impedance transformations in the 150- to 300-mc frequency band.

2. Self-Contained Bridge

Because of the above difficulties it was evident that an experimental coupler or sampling device, physically and electrically short, would have to be fabricated. Insertion of a small capacitive or inductive probe into a coaxial line section is perhaps the simplest method of coupling a signal out of the coaxial bridge. Such a coupler could be fabricated in a length of coaxial line short enough to avoid serious impedance transformations. However, the signal coupled into such a probe is related to the electrical position of the probe between the signal source and termination, and the output could vary considerably as the frequency is changed. In addition, no relative measure of the power transferred to the crystal load can be obtained because of the reflection coefficient of the termination.

Because of its directivity the signal coupled into a directional coupler is proportional to the power transfer in the line and is independent of the reflection coefficient of the terminating load if the second order terms are neglected.[3] This power measuring property is responsible to a large degree for the original decision to use directional couplers in the experimental bridge. Ideally, a dual coupler is needed to accurately measure the power dissipated in the crystal but a single coupler can be used with a lesser degree

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[3] Montgomery, C.G., et al, Technique of Microwave Measurements. Vol. II, M.I.T. Radiation Laboratory Series, McGraw-Hill, New York, 1947, p 854.

of accuracy. Power accuracies of better than 10 per cent can be obtained with single couplers if the voltage-standing wave ratio does not exceed two. Because of this ability to measure power it was decided to construct a bridge using directional couplers rather than the shorter, simple probes.

The bridge is designed as a compact self-contained unit which incorporates the crystal and VHF rheostat sockets directly into the coupler and thereby avoids the increased length necessitated by external coaxial connectors. The entire length of each leg from the socket through the coupler to the oscillator connection has been kept to less than 3 in., which should not cause any serious impedance transformation. The coupler itself is of the resistive loop type in which the capacity of the loop, the inductance of probe slot, the line termination and the resistor in the loop form a bridge arrangement which exhibits directional properties.[4] The design of the unit has been completed and the experimental model is presently being constructed.

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[4] Morrison, J.F. and Younker, E.L., "A Method of Determining and Monitoring Power and Impedance at High Frequencies," Proc. IRE, Vol. 36 (February 1948) p 212.

IV. CONCLUSIONS

Sufficiently accurate and sensitive power measurements have not yet been realized using directional couplers in the standards system. Satisfactory calibration of instruments limits the foreseeable accuracy of the standard crystal measurement setup to approximately 1 per cent. Lack of sufficient detector sensitivity also contributes to one of the principal sources of error in accurately determining the resonant resistance and frequency of crystals. A Marconi Type 1066A Signal Generator has been ordered. Available information indicates that this instrument will satisfy the immediate requirements of the project for a stable signal source.

Of the oscillators considered, the Plate Degenerative Oscillator appears to be best suited for use with the coaxial crystal parameter bridge. Tracking difficulties are eliminated by utilizing three models having overlapping frequency ranges to cover the frequency band from 150 to 300 mc/sec. Although the upper frequency limitation, when used with the bridge, has not as yet been determined, consistent operation has been obtained as a crystal oscillator at frequencies up to 325 mc/sec. No adjustment other than the initial balancing of C_o for each crystal is necessary in order to obtain crystal controlled operation over the tuning range of each unit.

Preliminary studies indicate that a calorimetric power measuring system utilizing a thermistor bridge is capable of measuring the power dissipation in VHF crystals. Use of a calorimetric system makes it possible to measure the power dissipation in the crystal without any electrical connection to the crystal parameter bridge. Matched thermistors in adjacent legs of the thermistor bridge provide ambient temperature compensation.

Because of their electrical length, all commercial directional couplers investigated were found to be unsatisfactory for use in the proposed coaxial crystal parameter bridge. For this reason a bridge is being constructed which utilizes single couplers and incorporates the crystal and VHF rheostat sockets directly into the coupler. This allows a reduction in the overall length from greater than 12 in. to less than 3 in. and should eliminate any serious impedance transformation effects.

V. PROGRAM FOR NEXT QUARTER

Work during the next quarter will be a continuation of that reported in the preceding pages, with emphasis on the following objectives:

1. construction and test of a coaxial bridge system utilizing the shorter directional couplers,
2. continued investigation of "active" oscillator circuits for use with the coaxial bridge,
3. construction and test of a thermistor bridge power measuring system,
4. development of a more sensitive null detector system for use with the crystal measurements standard,
5. procurement or development of an accurate voltage measurement device for use with directional couplers in the crystal measurements standard and
6. continued measurement of test crystals as new equipment is received or developed for use in the crystal measurements standard.

Respectfully submitted:

Douglas W. Robertson
Project Director

Samuel N. Witt, Jr.
Research Engineer

William R. Free
Assistant Research Engineer

Approved:

J. E. Boyd, Chief
Physical Sciences Division

VI. PERSONNEL

During this report period Mr. T. R. Scott resigned from the Engineering Experiment Station to accept a position with private industry. Mr. Scott's duties were assumed by Mr. William R. Free, Assistant Research Engineer, who was employed on September 10, 1956 on a full-time basis. Mr. Free is a graduate of the Georgia Institute of Technology and holds the degree of B.S. in Electrical Engineering. He served 3 years as an Electronic Technician in the United States Coast Guard and was associated with the Sperry Gyroscope Company for the last 3 years as an Electronic Engineer.

Mr. W. B. Warren, Assistant Research Engineer, was employed by this project on a part-time basis and is currently devoting one-fifth time to project work. Mr. Warren holds the degree of M.S. in Electrical Engineering from the Georgia Institute of Technology. He served 3 years as an Electronic Technician in the United States Navy and has been associated with this station on several projects since 1953.

Biographical sketches of the remaining key technical personnel was included in Progress Report No. 1. The time contributed by each during this period is:

Douglas W. Robertson	Project Director	Full-Time
Samuel N. Witt, Jr.	Research Engineer	1/3 Time
James E. Lane	Technical Assistant	1/5 Time

ENGINEERING EXPERIMENT STATION
of the Georgia Institute of Technology
Atlanta, Georgia

PROGRESS REPORT NO. 3

PROJECT NO. A-271

INVESTIGATION OF METHODS FOR MEASURING THE EQUIVALENT ELECTRICAL PARAMETERS OF QUARTZ CRYSTALS

By

DOUGLAS W. ROBERTSON, S.N. WITT, JR. and WILLIAM R. FREE

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CONTRACT NO. DA-36-039-sc-71191

DEPARTMENT OF THE ARMY PROJECT NO. 3-24-02-072
SIGNAL CORPS PROJECT NO. 867B

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15 OCTOBER 1956 TO 15 JANUARY 1957

PLACED BY THE U. S. ARMY
SIGNAL CORPS ENGINEERING LABORATORIES
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ENGINEERING EXPERIMENT STATION
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I. PURPOSE

The purpose of this project is threefold:

1. To study and investigate methods and techniques for measuring the equivalent electrical parameters of quartz crystal units in the frequency range of 150 to 300 mc/s, including:

   (a) A means for directly measuring the power drive of a crystal unit,

   (b) A simple and practical means of cancelling the capacitance of the crystal unit, C_o, at the test frequency, and

   (c) A means of measuring the effective resistance of the crystal unit at the series resonant condition.

2. To accumulate data from the investigations of 1. above, with a view of utilizing the information for the development of a practical test method for the frequency range 150 to 300 mc/s which will make it possible to:

   (a) Subject the crystal to any selected drive level between the limits of 0.2 and 4.0 milliwatts,

   (b) Measure crystal resistance values between the limits of 20 and 200 ohms,

   (c) Attain an accuracy of resistance measurement of ± 5 ohms or ± 10 per cent, whichever is greater, and

   (d) Attain an accuracy of resonant frequency determination within ± 0.001 per cent of the series resonant frequency of the crystal unit.

3. To study and investigate means for establishing a laboratory measuring technique to be used as a standard for measuring the equivalent electrical parameters of quartz crystal units in the frequency range of 100 to 300 mc/sec.

II. ABSTRACT

Incomplete investigations of the sources of inaccuracy in the proposed crystal measurements standard indicate that the instruments utilized are not sufficiently accurate for the intended purpose. Typical agreements, even for resistive standards are on the order of $\pm$ 5 percent for impedance magnitude and $\pm$ 5 degrees for phase angles.

Additional crystal circle diagrams indicating various characteristics of the measurements system are presented. These diagrams were obtained by using the newly arrived Marconi Type 1066/1 Signal Generator which is partially evaluated in this report.

The development of a more sensitive null detector system and the development of crystal drive level measuring equipment for use with the standard system have received further attention; however, this work is not sufficiently complete for definite conclusions.

An experimental thermistor bridge power measuring system was assembled and tested. The results obtained from the experimental system indicate that a system of this type should be capable of measuring crystal power dissipations over the range of 0.5 to 4.0 mw with an accuracy of $\pm$ 5 percent.

The experimental model of the coaxial Crystal Parameter Bridge was completed. Impedance matching within 15 percent for magnitude and 5 degrees for phase angle at drive levels as low as 0.5 mw have been obtained with the present unit.

Preliminary tests indicate that although satisfactory within themselves, when used in combination the Plate Degenerative Oscillator and the coaxial Crystal Parameter Bridge do not exhibit suitable characteristics to permit

measurement of crystal parameters. This defect is primarily due to the degradation by the bridge of the crystal phase and magnitude relations and to the manner by which the oscillator normally maintains crystal controlled oscillations.

III. CONFERENCES

On 28 November 1956, Dr. G. K. Guttwein and Mr. Dennis Pochmerski of SCEL visited the Engineering Experiment Station at Georgia Tech to observe and discuss the technical status of this project. Breadboard models of the Plate Degenerative Oscillator and the experimental setup for measuring the crystal power dissipation were demonstrated. The data and curves resulting from measurements made with the crystal standard system were reviewed and the necessity of instrument calibration was discussed.

Primary conference conclusions were as follows:

1. that the experimental tests on the recently fabricated coaxial Crystal Parameter Bridge be completed and tests initiated to determine the feasibility of using this bridge in conjunction with the Plate Degenerative Oscillator,

2. that additional r-f power measurements be made with the experimental power measuring system to adequately determine the accuracy and suitability of this method for measuring crystal power dissipation,

3. that certain standard impedances, being calibrated by the Bureau of Standards, will be made available to the project for the purpose of calibrating the commercial equipment used in the crystal standards system, and

4. that additional measurements of semi-standard impedances be made using various commercial bridges in order to determine the source of the inconsistences obtained.

IV. EXPERIMENTAL WORK AND CIRCUIT STUDIES

A. Crystal Measurements Standard

1. Introduction

All phases of the development of a Crystal Measurements Standard have continued except the laboratory development of a stable signal source. This latter work was discontinued early in this report period because of the promised delivery of a Marconi Type 1066/1 Signal Generator which was later received and partially evaluated for this report.

Principal efforts have been directed toward calibrations of various kinds. These problems have been approached by measuring crystal parameters as well as resistive termination parameters. Some conclusions have been reached concerning the consistency of data; however, little has been accomplished concerning the absolute accuracy of measurements. This was to be expected since accurately calibrated standards have not yet been made available to the project.

Some progress has been made toward accurately measuring crystal drive level, but the work is not sufficiently complete for a comprehensive evaluation.

Investigations of the GR Admittance Meter and the HP VHF Bridge to determine their suitability for standard crystal measurements have continued.

Data are presented concerning the performance of the APR-4 radar receiver tuning unit type TN-17 as a sensitive null detector. Poorer sensitivity than was expected as well as spurious responses have been observed. However, construction of an adequately sensitive null detector system using this tuning unit appears practical.

Much overlapping will be observed between the following sections since many of the measurements had more than one objective. The section on experimental data is broadly concerned with crystal measurements while data in other sections are more specifically related to particular problems.

2. Experimental Data

Additional data on crystal number 2-W have been obtained using the Marconi Type 1066/1 Signal Generator over the frequency range from 125 to 425 mc/sec. The Marconi Signal Generator was found to be adequately stable in most cases for making crystal measurements to frequencies beyond 300 mc/sec (see page 13). A consequence of better signal generator stability was smoother crystal circle diagrams, as may be seen by observing some of the curves presented herein.

Figure 1 shows a set of circle diagrams for crystal number 2-W for the 5th through the 17th overtones. These measurements were made using the setup shown in Figure 1 of Progress Report No. 2 except that the HP model 608A Signal Generator was replaced by the Marconi Signal Generator. Figure 2 shows a block diagram of the present setup.

The actual data points are not shown in Figure 1; however, the curves were drawn through every point obtained with the exception of those associated with spurious modes. Frequency readings up through 275 mc/sec were also recorded for the curves shown in the figure. The frequency distribution verified that the curves shown were the principal overtone responses. Above 325 mc/sec, the frequency could not be recorded with the equipment available. However, measurements of various possible resonances due to line lengths and crystal capacitance indicated that the responses shown were actually the crystal responses even at 425 mc/sec.

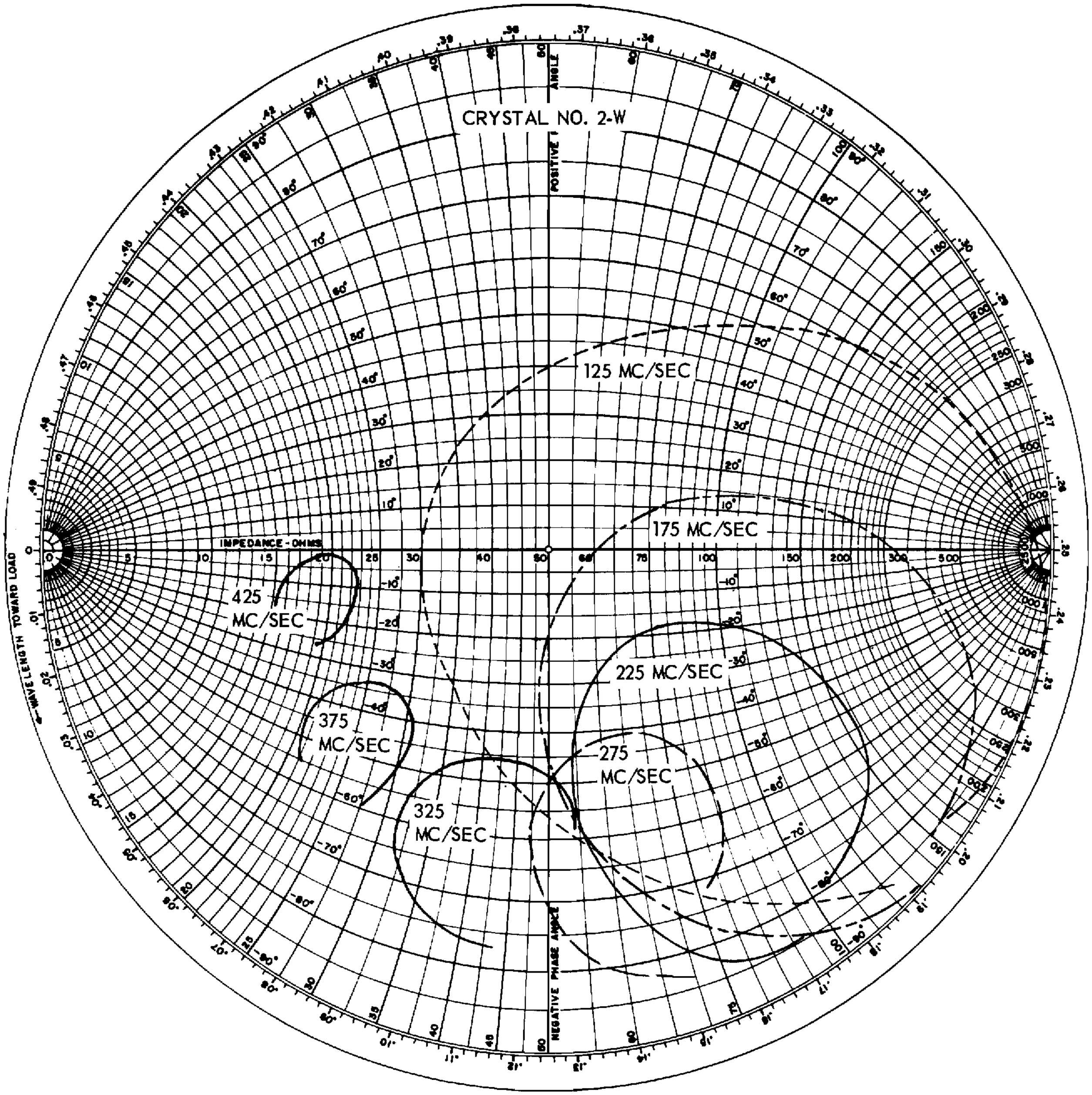


Figure 1. Overtone Responses of Crystal 2-W.

Figure 3 shows several circle diagrams for crystal 2-W obtained with varying line lengths. These measurements were made to partially determine the calibration accuracy and resolution of the GR Admittance Meter as well as to evaluate the necessity of using a calibrated line length. The curves for the

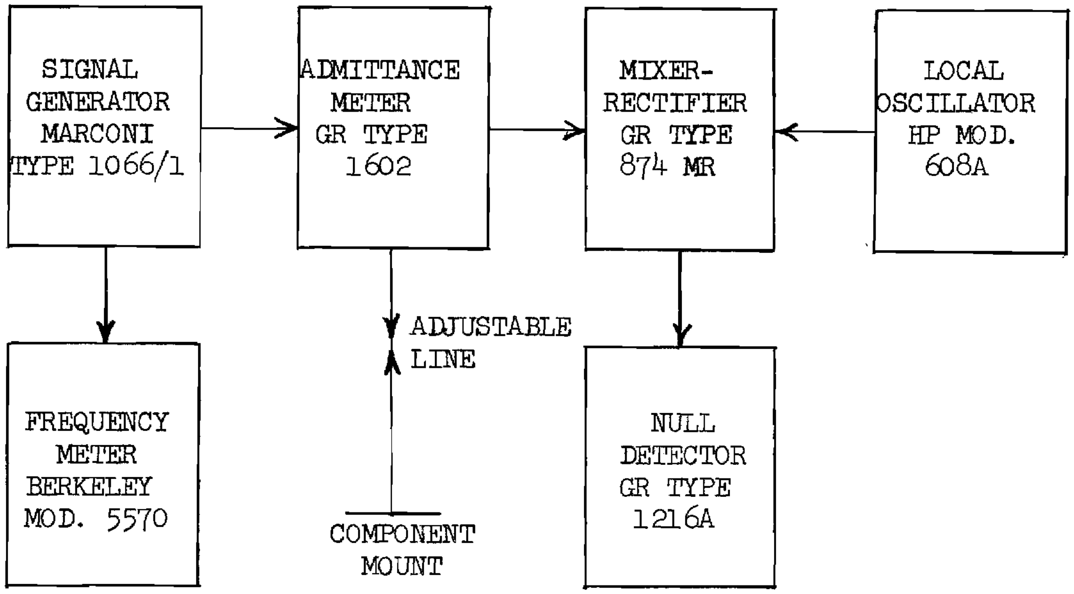


Figure 2. Present Laboratory Measurements Standard Setup.

30-cm line length (0.22λ) and for the minimum line length (0.05λ) have been rotated into the half-wavelength line position for direct comparison with the half-wavelength and full-wavelength line measurements. The original positions of these curves are also shown. As may be seen, when the line length was such that the original circle fell at high values of conductance or susceptance (or small impedance values on the Z-Θ charts) the inaccuracies were increased as indicated by the disagreements between this circle and circles obtained for other line lengths. This was to be expected because of the limited resolution

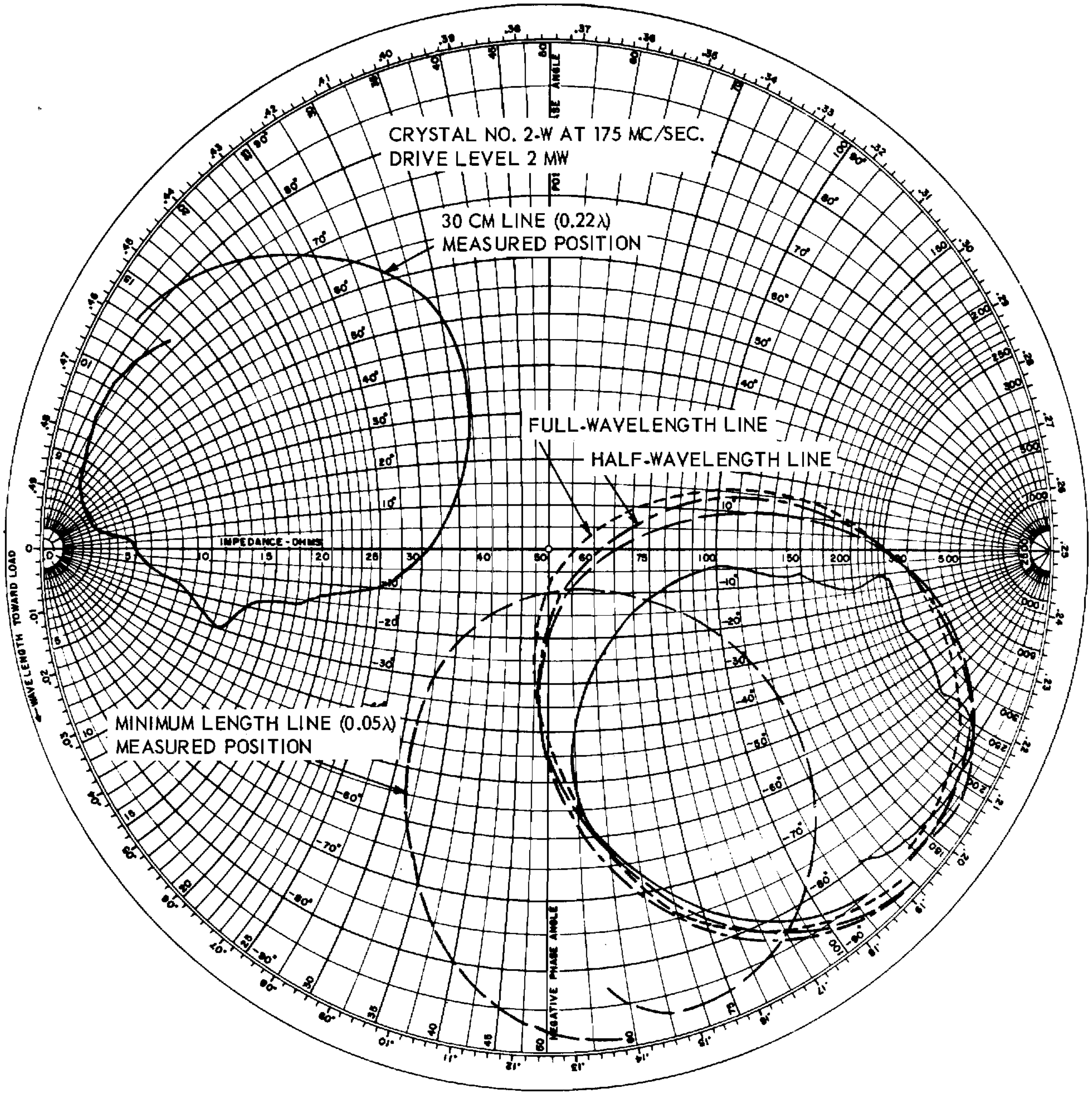


Figure 3. Measurements on Crystal 2-W for Different Line Lengths.

of the admittance meter at high conductance and susceptance readings. Thus it is generally desirable to use line lengths which provide readings in the lower range of admittance values. At the higher overtones, even a half-wavelength line may produce circles in this undesirable region as shown in Figure 1 (all curves of which correspond to a half-wavelength line), so it is often desirable to use line lengths other than a half-wavelength. For example, the line may be shortened to have an effect similar to cancelling C_o. This shortening of the line apparently does not greatly affect the accuracy of measurements as long as the results are properly interpreted.

A curve is also shown in Figure 3 for a full-wavelength line. As may be seen, the curve is very close to that obtained for the half-wavelength line as would be expected for an essentially lossless line. It is obvious though that, if a sufficiently large number of half-wavelength sections were used, additional corrections would have to be applied to account for the variation in line length over the small range of frequencies involved in a single crystal response.

Figure 4 shows circle diagrams obtained for crystal number 2-W at 175 mc/sec for two different drive levels adjusted by voltmeter measurements across a resistive termination. Although the power level variation is not great enough to yield conclusive results concerning the crystal, it is evident that power level variations do not appreciably affect the accuracy of measurements made on this crystal from day to day. Thus this factor can be eliminated as a possible source of inconsistency in data.

Figure 5 shows a superposition of several curves obtained for crystal number 2-W over a period of several months. As may be seen, the agreement between

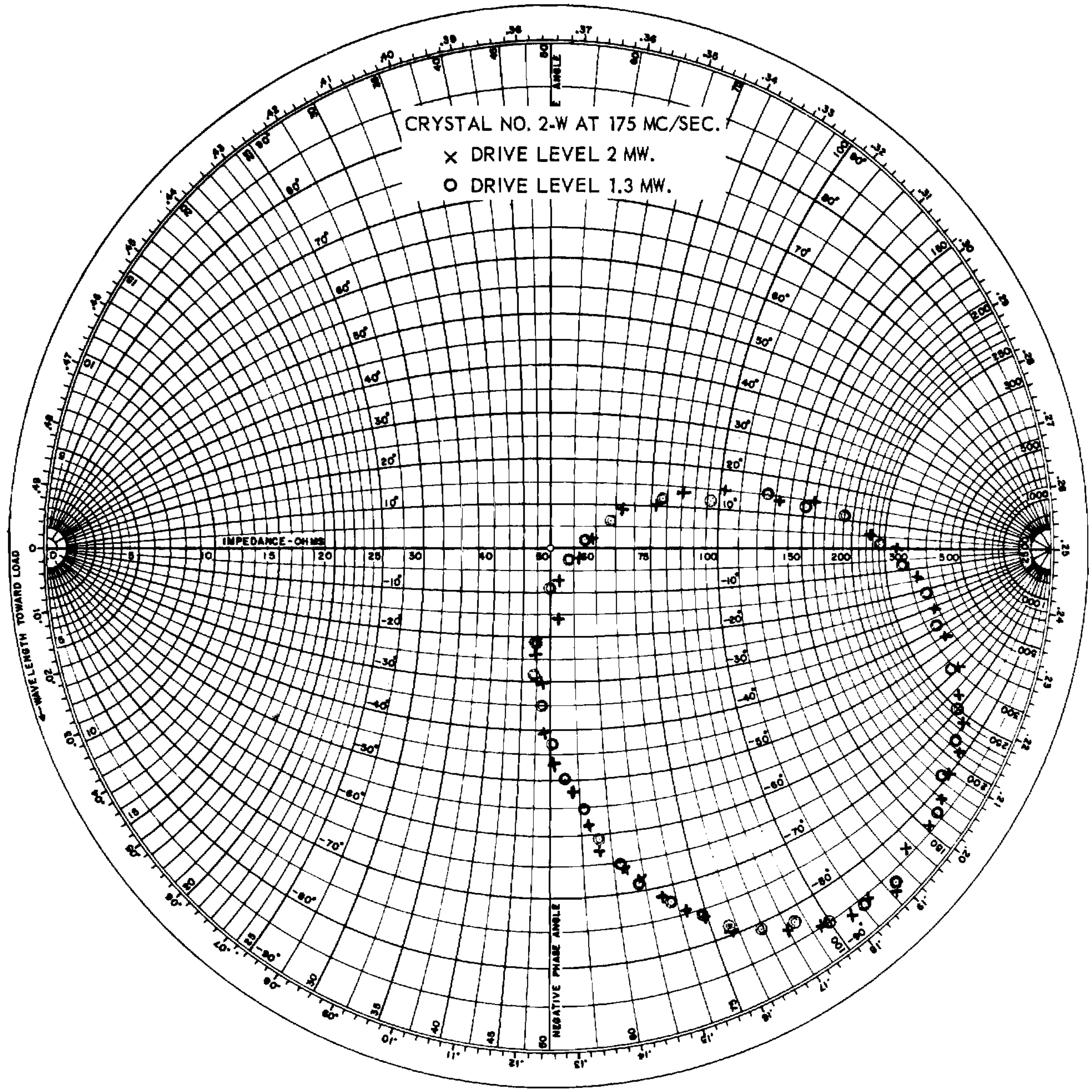


Figure 4. Effect of Drive Level on Crystal 2-W at 175 Mc/sec.

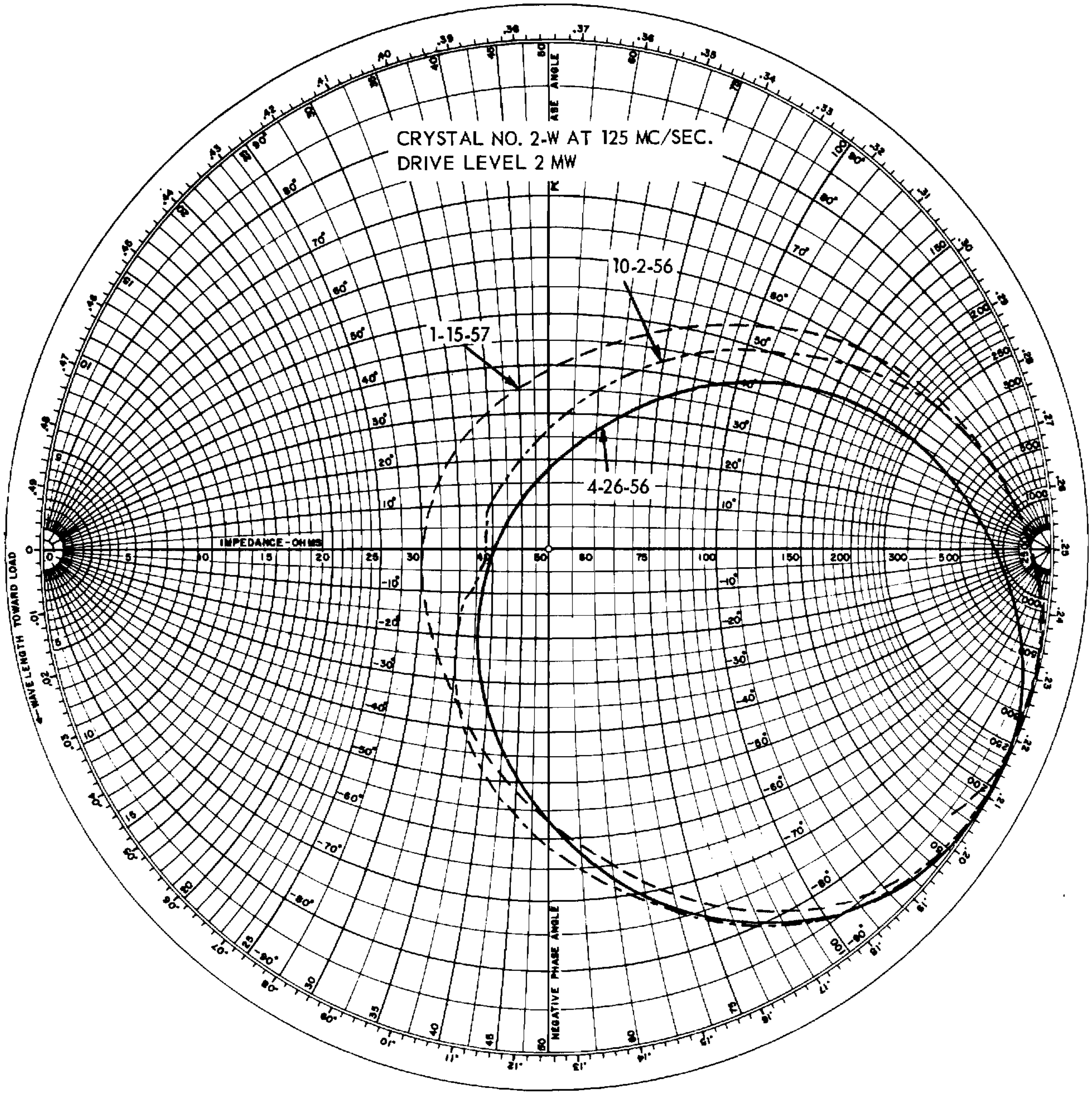


Figure 5. Cumulative Data on Crystal 2-W Over a Several Months Period.

the curves is poor. This does not necessarily indicate measurement errors, however, since it is very possible that the crystal parameters may have changed during the intervening time. It is also possible, of course, that the admittance meter calibration may have changed some during this time. CI Meter measurements on crystal number 2-W have indicated that the resonant resistance has decreased, although not as much as indicated by Figure 5. Many other measurements separated by periods of several days have shown almost perfect agreement among the curves.

3. Stable Signal Generators

Laboratory work on the development of a stable signal generator to cover the frequency range from 100 to 300 mc/sec was discontinued early in this report period because of the promised delivery of a Marconi Type 1066/1 Signal Generator. This generator was received during the last week of December.

Preliminary investigations of the frequency stability of the Marconi generator indicated that it will be sufficiently stable for most crystal measurement purposes. The stability was determined by beating the output of the generator against a stable frequency source at frequencies near 200 mc/sec. Sample recordings of the resulting audio frequency beats are shown in Figures 6-9.

It was found that the generator reaches its ultimate stability after one to two hours of operation. Most of the initial drift occurred in the first 30 minutes of operation during which time the generator was not sufficiently stable for crystal measurements. It was also found that changing the frequency by an appreciable amount (more than a few percent of the dial reading) usually resulted in increased drift. For example, after $1\frac{1}{2}$ hours warm-up, the frequency was changed from 200 to 175 mc/sec. The initial drift rate after the frequency change was 0.75 kc/min decreasing to 140 cps/min 30 minutes later. Figure 6 shows the frequency drift 116 minutes after the frequency change. The frequency was still changing at the average rate of 50 cps/min. Figure 7 shows the drift 312 minutes after the frequency change. Here it will be observed that the drift was of a short-term nature and that the average drift was essentially zero. This curve shows that typical short-term peak variations as great as 200 cps may be expected during any one minute interval with occasional variations as great as 500 cps/min.

Figure 8 shows a selected portion of a recording obtained on a different day from that of the above described operation. This curve represents about the best stability obtainable and occurred after 320 minutes of warm-up time.

It was found that the generator would occasionally assume a long-term drift even after several hours of warm-up. Figure 9 shows a portion of a recording made 6 hours after the signal generator was turned on. Although a long-term drift was apparent the average drift rate in this case was still less than 100 cps/min.

In obtaining all of the above recordings, isolating attenuators were used between the signal generator and the standard being used for comparison. However, when the beat frequency became less than 1000 cps, a tendency for pulling of the signal generator frequency was observed. A similar tendency was also observed when the signal generator was used as a source for the measurement of crystal parameters. This was objectionable at certain points on the crystal circle diagram as it made the frequency more difficult to adjust to specific points.

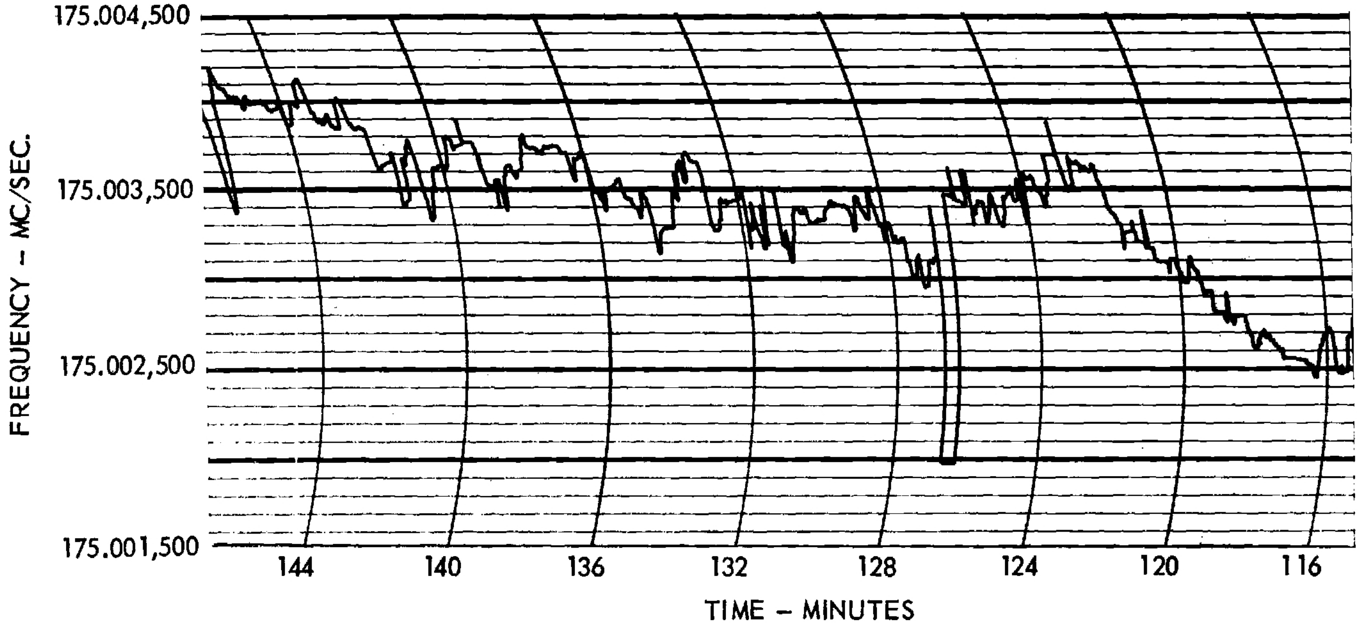


Figure 6. Drift of Marconi Type 1066/1 Signal Generator 116 Minutes After a Frequency Change.

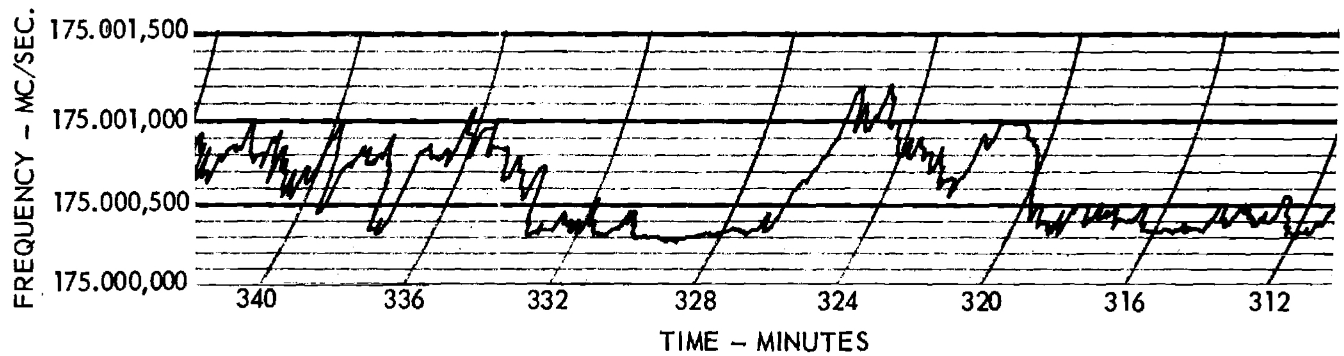


Figure 7. Drift of Marconi Type 1066/1 Signal Generator 312 Minutes After a Frequency Change.

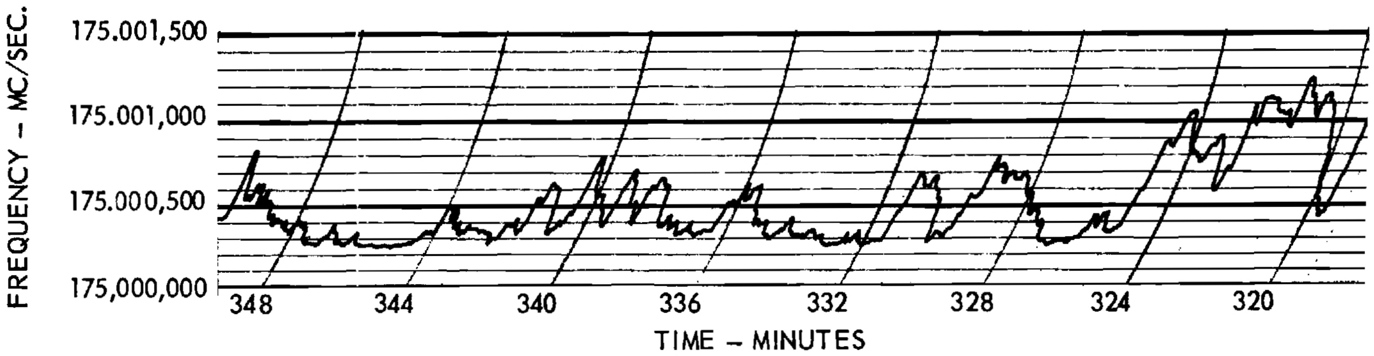


Figure 8. Best Stability Obtained From the Marconi Type 1066/1 Signal Generator.

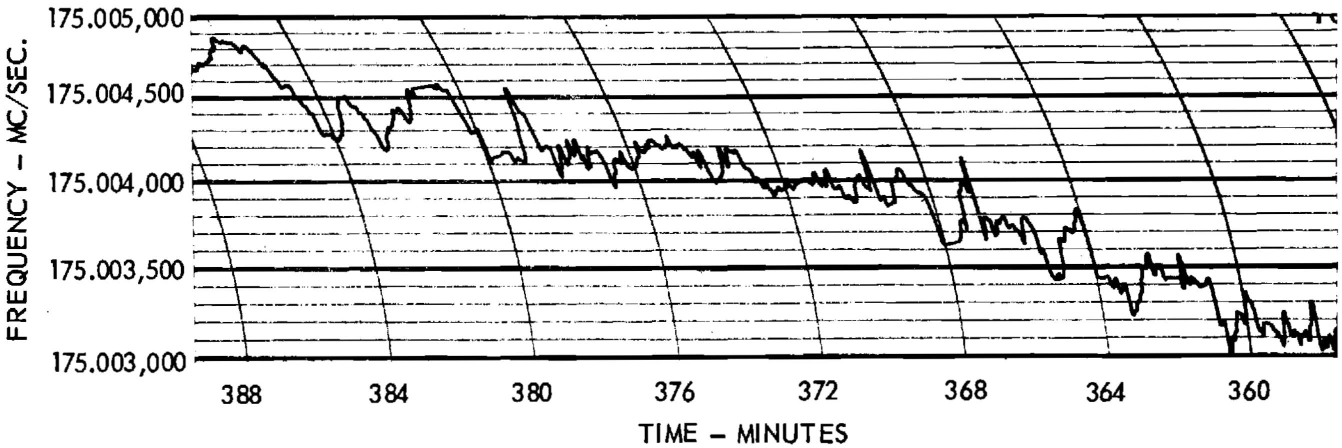


Figure 9. Spurious Long-Term Drift of the Marconi Type 1066/1 Signal
Generator After 6 Hours of Warmup.

The rated output voltage (0.1 volts) was not sufficient to obtain a 2-mw drive level with most crystals, thus necessitating the use of an amplifier. Wide-band chain amplifiers have been satisfactorily used at frequencies as high as 200 mc/sec. It is planned, however, to investigate the use of television booster amplifiers which may be usable at frequencies from 100 to 300 mc/sec with slight modifications. The use of an amplifier provides the additional advantage that the above mentioned pulling effect is greatly decreased.

The use of the FINE TUNING control and INCREMENTAL FREQUENCY controls were investigated for obtaining small frequency changes. The FINE TUNING control was found to be the more suitable. If the FINE TUNING control is used, the INCREMENTAL FREQUENCY selector should be turned to the off position since the incremental frequency circuits were found to introduce additional instabilities when in operation.

Line regulation of the power source was not used in collecting the above data. It is believed that some of the short-term frequency variations may be caused by line transients. It is planned to obtain additional data on the generator using an electronic line regulator.

In general, the Marconi Signal Generator appears to be very suitable for use in making crystal parameter measurements. As may be seen from the above data, the generator appears to surpass the manufacturer's stability claims.

4. Power Measurements

For the crystal measurements previously presented, power was estimated by measuring the r-f voltage across a substitution resistor. Several other methods of measuring power have been considered, but as yet none of the methods have been developed to a point where they are useful for accurate measurements.

The proposed power measuring system which is presently receiving the most attention is illustrated in Figure 10. The necessity of each component is best described by considering the setup procedure which is illustrated by the following steps.

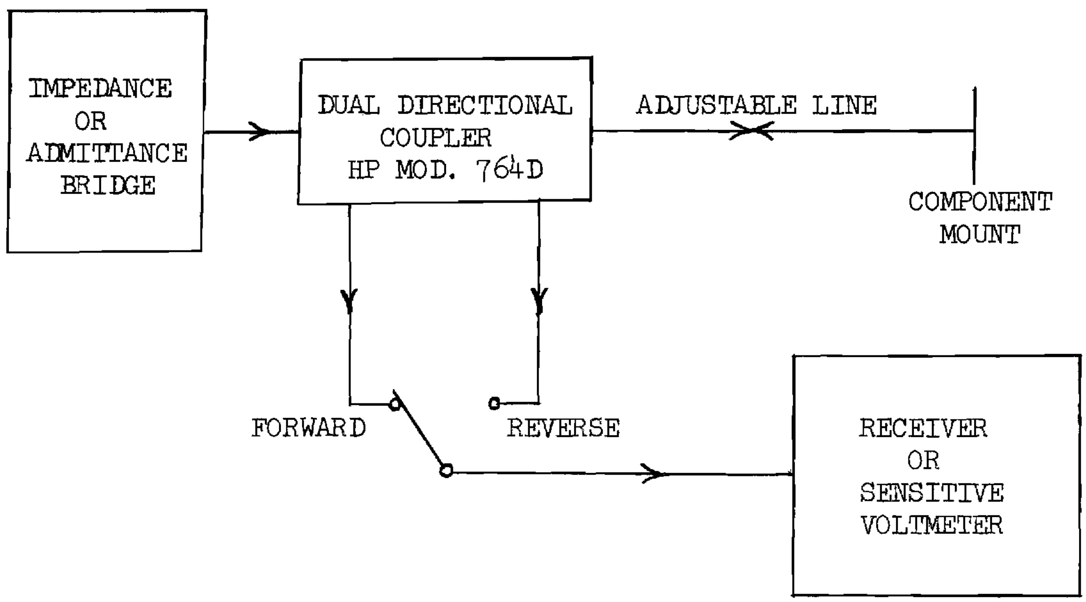


Figure 10. The Proposed Power Measuring System.

a. Set the adjustable line to the proper length as required for crystal measurements with the directional coupler in the line as shown.

b. Determine the approximate crystal impedance at the point where the greatest accuracy of power measurement is required.

c. Replace the crystal with an accurate power measuring device which terminates the line in the impedance measured in b.

d. Set the signal generator to the required power level as indicated by the power level measuring device.

e. Record the receiver readings (V_1 and V_1') on the two directional coupler outputs.

f. Replace the power measuring device by the crystal.

g. Readjust the signal generator output for the correct net forward power as indicated by the receiver (i.e., $V_2^2 - V_2'^2 = V_1^2 - V_1'^2$).

The needs for the various pieces of equipment described above are indicated by the following facts and/or assumptions:

a. Crystal drive levels must be measured accurately over the range of 0.2 to 4 mw for the entire frequency range.

b. Directional couplers or similar devices must be used to provide continuous power level monitoring while crystal impedance measurements are being made.

c. The minimum acceptable attenuation of the directional couplers must be approximately 20 db to limit errors introduced in the crystal impedance measurements, indicating that power levels from the directional outputs of the directional couplers will be on the order of 2 to 40 microwatts.

d. When used with varying load impedances and frequencies, presently available directional couplers are not sufficiently accurate. Also, terminating power level meters which will accurately measure powers in the microwatt range are not presently available.

e. The consistency of directional couplers and various sensitive voltmeters (receivers) is satisfactory provided the equipment can be calibrated shortly before use.

f. Power level meters which will measure power levels in the milliwatt range with sufficient accuracy are available (or can be constructed).

Accordingly, it is planned to calibrate a system consisting of directional couplers and a receiver (or other voltmeter) so that greatest accuracy is obtained in the power level and impedance range of greatest interest immediately prior to making crystal impedance measurements. However, this system is not without disadvantages. For example, the receiver (or voltmeter) indicated in e above, although commercially available, is not presently available to the project. Also, the truth of statement f above is questionable although some manufacturers literature indicates that such power measuring equipment is available.

As indicated in Chapter IV, section B, appreciable effort has been expended toward developing a device capable of accurate power level measurements in the milliwatt region. Although this device is intended primarily for the CI Meter bridge, it may also be used as the power level meter mentioned in f above if sufficient accuracy can be obtained.

In this connection, a thermistor has been inserted into a GR Type 874 50-ohm termination. Initial data indicate that the temperature rise produced by 2 mw of r-f power is so small as to be completely masked by ambient temperature variations. However, further experimentation using thermal isolation is planned. It has been found that the insertion of the thermistor into the termination does not materially affect the r-f properties of the termination. Thus, direct comparison between r-f and d-c power should be possible if the problems of ambient temperature variations can be overcome.

Further investigations of the influence of the dual directional coupler on the accuracy of impedance measurements were made. Figure 11 shows crystal impedance diagrams at three frequencies both with and without the directional coupler in the line between the admittance meter and the component mount. The figure shows the directional coupler to have negligible effect at these frequencies.

Measurements on fixed resistive terminations have been made both with and without the dual directional coupler using the HP Model 803A VHF Bridge. However, as will be shown later in Figures 13 and 14, the results, even without the coupler, were so poor as to make an evaluation of the coupler impossible.

In general, the directional coupler had only slightly more effect on the measured impedances than an equivalent length of high quality rigid coaxial line at most frequencies in the range from 100 to 300 mc/sec. It should be mentioned that the coupler tested was designed for use between the frequency limits of 216 to 450 mc/sec. The directivity is affected considerably at frequencies below 200 mc/sec as are the outputs from the directional arms. It appears, however, that the device may still be useful for power measurements down to 100 mc/sec by applying the proper calibration procedure as outlined above.

5. Detector Systems

Work has continued on the development of a more sensitive null detector system. A type TU-17 tuning unit (designed for use with the AN/APR-4 radar search receiver) covering the frequency range from 75 to 300 mc/sec has been mounted independently of the receiver for use with various i-f amplifier systems. A summary of results obtained to date is shown in Figure 12 where

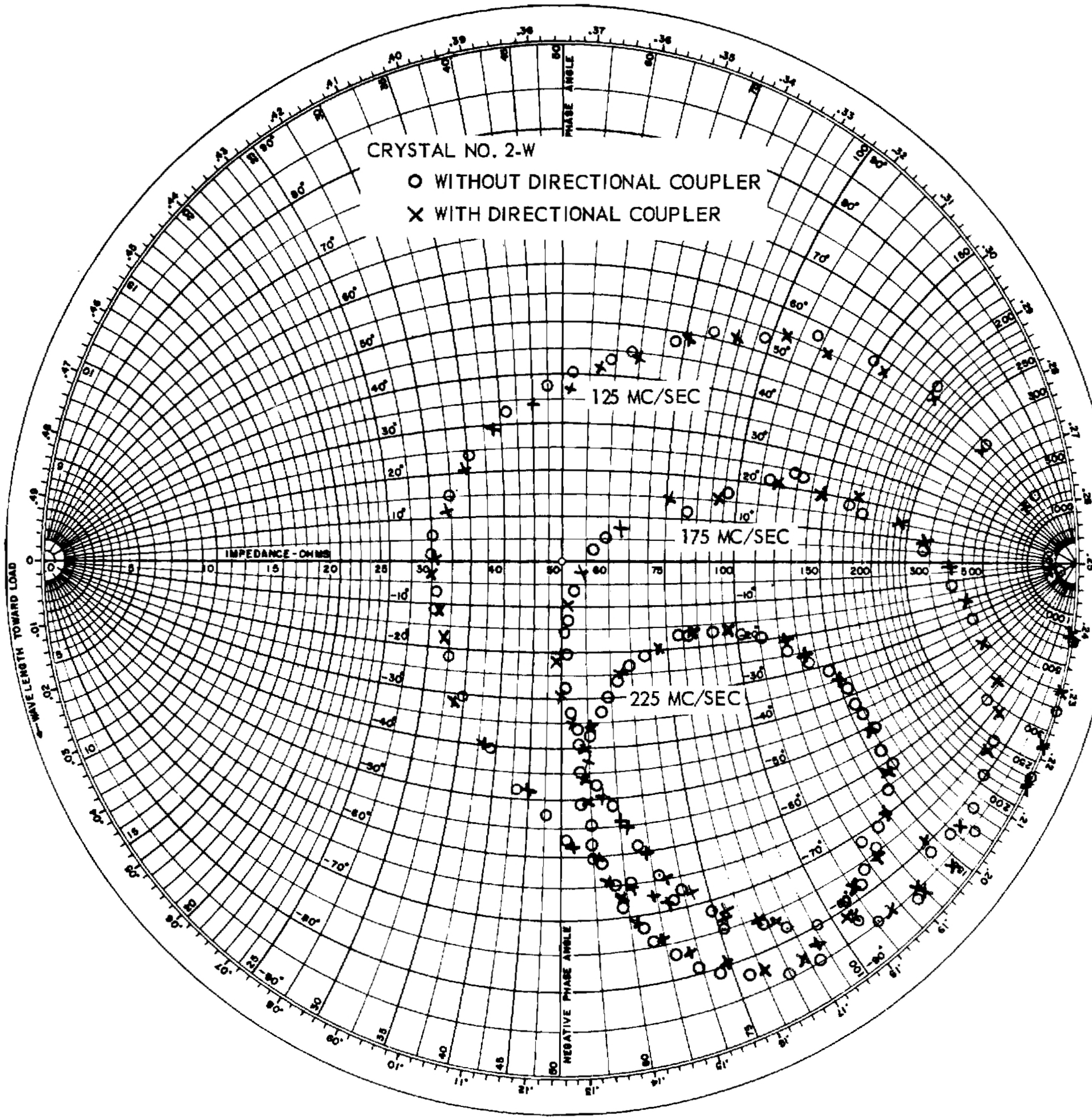


Figure 11. Effects of Directional Coupler on Impedance Measurements.

the tuning unit performance is compared with that of the mixer-rectifier i-f amplifier system previously reported.

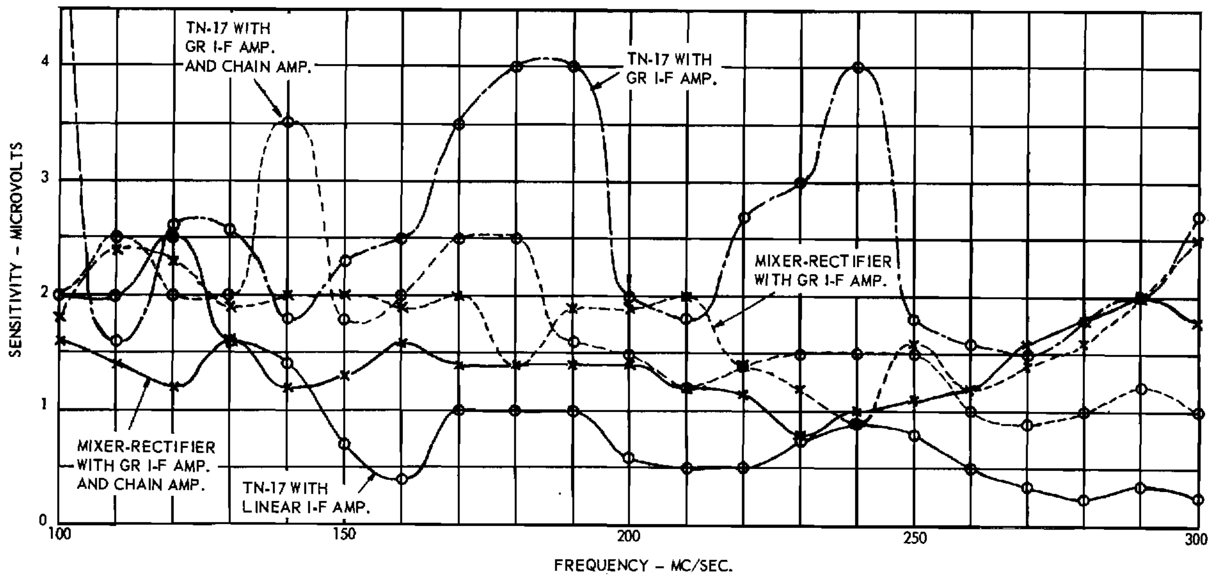


Figure 12. Sensitivity of Several Detector Systems.

The ultimate sensitivity is, of course, a function of impedance level and bandwidth which determine the input noise level. The present sensitivity is limited primarily by the i-f amplifier noise. This noise can be decreased by reducing the bandwidth; however, this would make tuning more critical until the usefulness of the system would be destroyed by the local oscillator instability. This limitation has not yet been reached, however, and it appears that sensitivities on the order of 0.1 microvolt can be obtained over most of the range from 100 to 300 mc/sec without critically small bandwidths.

Although the sensitivity is not appreciably greater, one advantage of the APR-4 tuning unit over the mixer-rectifier system is that some preselection at the r-f frequency is obtained which helps to eliminate some of the spurious responses caused by mixing of harmonics of the input signal with harmonics of the local oscillator.

A disadvantage of the present tuning unit system is that many spurious oscillations and responses have been observed. These are apparently caused by coupling between the i-f amplifier and tuning unit through the supply voltage leads. When isolation filtering was added, the amplitudes of the spurious responses were decreased but the responses were not entirely eliminated. Additional bonding and shielding will probably be required.

6. Impedance Calibrations

During this report period, efforts have been made to establish the reliability of measurements made using the HP Model 803A VHF Bridge. Consistency was of greater interest than absolute accuracy for the first runs made. Therefore, repeated measurements were made for comparison using 100-ohm and 200-ohm terminations of the GR 874 type. The results of typical measurements are shown in Figures 13 and 14. These figures show the results of two measurement runs, one of which was performed 7 weeks after the other. All curves have been corrected for line length using the standard Z-θ charts and the measurements made on a short circuit. Additional curves are shown which include corrections for difference in length between the short circuit and terminations (See instruction sheets accompanying terminations.) as well as corrections made possible by the calibration charts provided with the bridge.

The claimed accuracies of the bridge with proper corrections applied are $\pm$ 2 percent for impedance magnitude and 1.2 degrees for the phase angle. The tolerance of the terminations is one percent at a very low phase angle. Thus

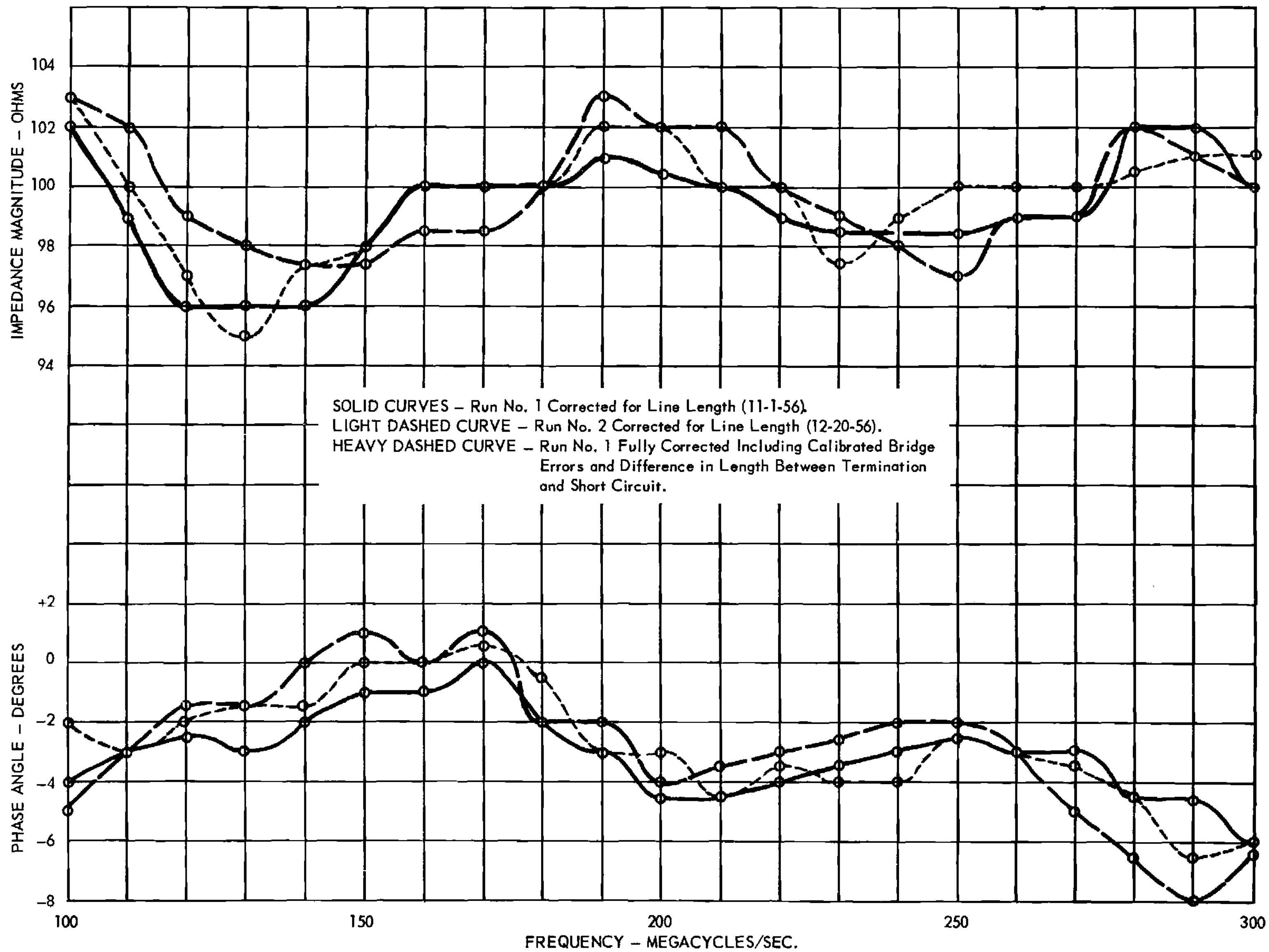


Figure 13. HP VHF Bridge Measurements on the GR 100-Ohm Termination.

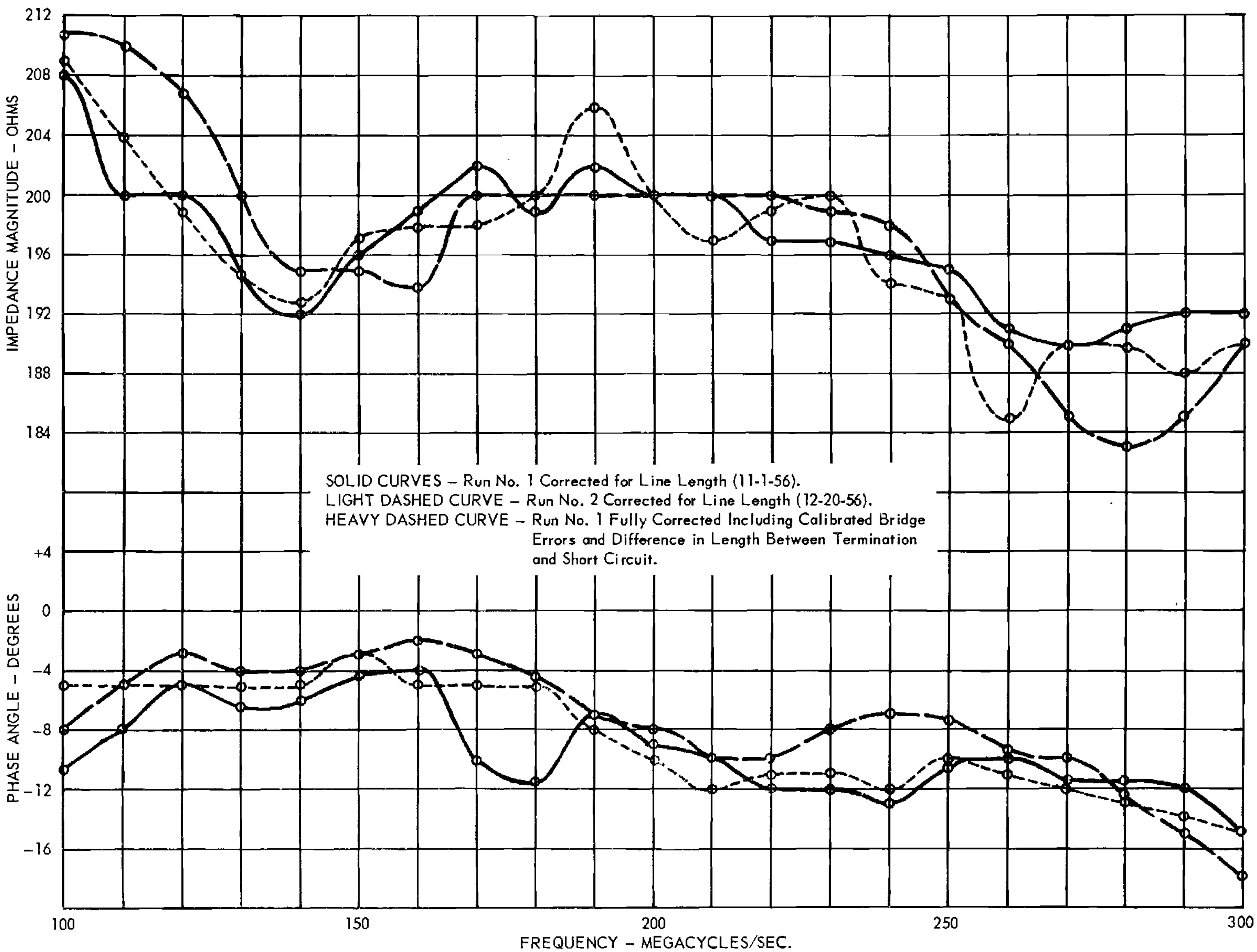


Figure 14. HP VHF Bridge Measurements on the GR 200-Ohm Termination.

the total maximum error should be about $\pm$ 3 percent for the impedance magnitude and $\pm$ 1.5 degrees for the angle. However, Figures 13 and 14 show that the accuracy with all corrections applied was generally no better than when only line length corrections were applied. A study of the system leads to several possible sources of error, the most important of which are:

a. human errors in reading the VHF bridge,

b. errors caused by poor null indication,

c. drift in the bridge, terminations or other elements with time,

d. errors in calibration of the terminations,

e. errors inherent in the methods of applying corrections to the readings, and

f. errors in bridge calibration.

A systematic procedure has been adopted for evaluating each of these possible errors. The first three have been evaluated by making repeated measurements after both long (several weeks) and short (several minutes) periods of time and then comparing the uncorrected bridge readings. Data from two runs on the 100-ohm termination and four runs on the 200-ohm termination yield conservative estimates of maximum total error due to the first three listings above of $\pm$ 2 percent for impedance magnitude and $\pm$ 0.5 degrees for phase angle. (These values are not much larger than the dial resolution of the bridge.) These errors are generally irreducible with the present equipment.

It has not been possible to check item d of the list of errors since accurately calibrated terminations have not yet been received by the project. However, as mentioned above, the GR terminations used with the bridge are claimed to be within $\pm$ 1 percent for impedance magnitude and to have a very low phase angle for frequencies to beyond 300 mc/sec. As discussed in a recent conference, the project is anticipating the arrival from SCEL of standards calibrated by the National Bureau of Standards.

Other calibration measurements have been made using a dual directional coupler and also various line lengths between the bridge and the terminations. Since the total line length when the directional coupler was used was one-fourth-wavelength at 165 mc/sec, errors in this region were to be expected. However, errors in impedance magnitude as great as 20 percent appeared at 280 mc/sec, a point where the short circuit measurements were very regular. This error cannot be attributed directly to the directional coupler since it has been found to have little effect on measurement on other occasions. Such large errors are at present unexplained.

The method of subtracting the line length within the bridge, which makes use of Z-θ charts, may introduce some appreciable errors. This possibility results from the very limited resolution of the charts and also obvious nonlinearities in the particular charts used by the project. It is planned to check for this source of error by mathematically subtracting the short circuits when personnel time permits. A study of Figures 13 and 14 indicates that the peak differences between the curves obtained on different days may be attributed to errors a through e of the above list. The maximum error differences are $\pm$ 3.5 percent for impedance magnitude and $\pm$ 3.5 degrees for phase angle.

The remaining errors, that is, the general trend of the curves, in Figures 13 and 14 may most likely be attributed to errors in bridge or termination calibration. After precisely calibrated standards are received, it will be possible to determine the calibration error of the bridge; however, it is not likely that suitable calibration curves can be prepared for all impedances because of the great personnel time involved in such a calibration procedure.

The total errors indicated by Figures 13 and 14 are far greater than the desired maximum errors for crystal measurements. This indicates that each of the errors must be reduced or a different system having less error must be found.

The GR Admittance Meter has been used more often than the HP VHF Bridge for making actual crystal measurements because of its greater sensitivity at the detector output. However, the Admittance Meter has not yet been fully checked for calibration using fixed resistive terminations. Initial measurements using the GR terminations with the Admittance Meter indicate that the calibration of the meter is fairly accurate. This is to be expected since it is probable that terminations of this type were used in the factory calibration of the Admittance Meter. Accordingly, more accurately calibrated standards must be obtained before general statements concerning the Admittance Meter can be made.

B. Power Measurements

1. Introduction

The experimental thermistor bridge power measuring system described in Progress Report No. 2 was assembled to determine the feasibility of using this type system to measure the power dissipation in VHF crystals. Glennite type 32CH1 thermistors were used as the heat sensing elements.

The thermistors were mounted in adjacent legs of the bridge to provide ambient temperature compensation. However, the null indicator deflections due to ambient temperature variations were of sufficient magnitude to make it impossible to maintain bridge balance at the desired sensitivity. This condition was primarily due to the inability to obtain properly matched thermistor pairs from the limited quantity of thermistors available. Inquiries have been made to several sources to determine the possibility of obtaining thermistor pairs matched to the desired degree of accuracy. Meanwhile, a temporary solution to the problem was obtained by decreasing the sensitivity of the null detector until the deflections due to ambient variations were reduced to an allowable magnitude. This eliminated the ambient difficulties, but, at the same time, the minimum power that the system was capable of measuring was increased from 0.2 mw to 0.5 mw.

2. System Error Calibration

A number of d-c power measurements were made to determine the errors in the system due to heat transfers. These measurements were made with d-c power applied to both VHF Rheostats in order to eliminate any errors due to r-f power. Specific amounts of d-c power ranging from 0.5 mw to 4.0 mw were applied to the Test VHF Rheostat (R_1) and the bridge was rebalanced by applying d-c power to the Reference VHF Rheostat (R_2). Representative data from this calibration setup is shown in Table I.

Defining the system error as $\left[\left(\frac{\text{Power in } R_2}{\text{Power in } R_1} - 1\right) \times 100\right]$ percent, these data indicate that a consistent, average error of + 32 percent exists in the system. Apparently this error is due to differences in bonds between the thermistors and the resistive films. Because of the extremely small size of the thermistor, identical bonds could not be reproduced and the resulting difference in the heat conductivity of these bonds was considerable. To substantiate this possibility the thermistors were removed and rebonded. A shift in the consistent average error to - 20 percent was apparent from the data obtained with the new bonding conditions indicating that these consistent errors are due primarily to the differences in bondings. Table II shows a comparison of representative data obtained for two different bonding conditions.

The resistance of the VHF Rheostats were varied relative to each other to determine the effect of various ratios of R_1/R_2 on the d-c measurements. Data obtained from these tests are shown in Table III. These data indicate that the error of the system varies as the R_1/R_2 ratio varies. This condition is apparently caused by the poor heat conductivity of the resistive films. For example, if R_1 and R_2 were both set at 50 ohms and 3.0 ma was passed through R_1, it was necessary to pass 2.7 ma through R_2 to balance the bridge, but if R_1 was retained at 50 ohms and R_2 increased to 100 ohms it was necessary to pass 2.2 ma through R_2 to balance 3.0 ma in R_1. This indicates that very little of the heat generated in the additional 50 ohms of R_2 was transmitted to the thermistor. This condition may be compensated for by maintaining the Reference Rheostat at a constant resistance value and obtaining a correction factor for each R_1/R_2 ratio from a calibration chart such as shown in Figure 15. However, if the R_1/R_2 ratio is maintained constant by adjusting the Reference Rheostat to the same resistance as the Test Rheostat, the error of the system would be constant and could be included in the system calibration.

3. R-F Power Measurements

A number of measurements were made by applying r-f power to R_1 and balancing the bridge with d-c power into R_2. The Test Rheostat was compensated

TABLE I

SYSTEM ERROR FOR FIRST BONDING CONDITION

$R_1 = R_2 = 50\Omega$				$R_1 = R_2 = 100\Omega$			
Power in R_1 (mw)	Power in R_2 (mw)	System Error (%)	Normalized System Error (%)	Power in R_1 (mw)	Power in R_2 (mw)	System Error (%)	Normalized System Error (%)
0.34	0.50	+ 32.5	+ 0.5	0.32	0.50	+ 35.0	+ 3
0.68	1.00	+ 31.5	- 0.5	0.67	1.00	+ 32.5	+ 0.5
1.05	1.50	+ 30.0	- 2.0	1.00	1.50	+ 32.3	+ 0.3
1.30	2.00	+ 35.0	+ 3.0	1.36	2.00	+ 32.0	0.0
1.68	2.50	+ 32.8	+ 0.8	1.76	2.50	+ 29.5	- 2.5
2.05	3.00	+ 31.7	- 0.3	2.20	3.15	+ 30.0	- 2.0
2.38	3.50	+ 32.0	0.0	2.40	3.50	+ 31.5	- 0.5
2.68	4.00	+ 33.5	+ 1.5	2.80	4.00	+ 30.0	- 2.0

TABLE II

COMPARISON OF SYSTEM ERRORS FOR FIRST AND SECOND BONDING CONDITIONS

FIRST BONDING $R_1 = R_2 = 50\Omega$				SECOND BONDING $R_1 = R_2 = 50\Omega$			
Power in R_1 (mw)	Power in R_2 (mw)	System Error (%)	Normalized System Error (%)	Power in R_1 (mw)	Power in R_2 (mw)	System Error (%)	Normalized System Error (%)
0.34	0.50	+ 32.5	+ 0.5	0.45	0.37	- 19.0	+ 1.0
0.68	1.00	+ 31.5	- 0.5	0.80	0.65	- 19.0	+ 1.0
1.05	1.50	+ 30.0	- 2.0	1.25	1.01	- 19.0	+ 1.0
1.30	2.00	+ 35.0	+ 3.0	1.80	1.51	- 16.0	+ 4.0
1.68	2.50	+ 32.0	+ 0.8	2.45	1.95	- 21.5	- 1.5
2.05	3.00	+ 31.7	- 0.3	3.20	2.50	- 22.0	- 2.0
2.38	3.50	+ 32.0	0.0	4.05	3.10	- 23.0	- 3.0
2.68	4.00	+ 33.5	+ 1.5	5.00	4.05	- 19.0	+ 1.0

so that the reactance was $50\underline{/\ 0.8}$ at 165 mc/sec. This was done to assure that the Rheostat presented a resistive 50-ohm load to the Hewlett-Packard, type 608C, VHF Signal Generator. This allowed the amount of r-f power applied to the Test Rheostat to be calculated from the signal generator attenuator dial reading.

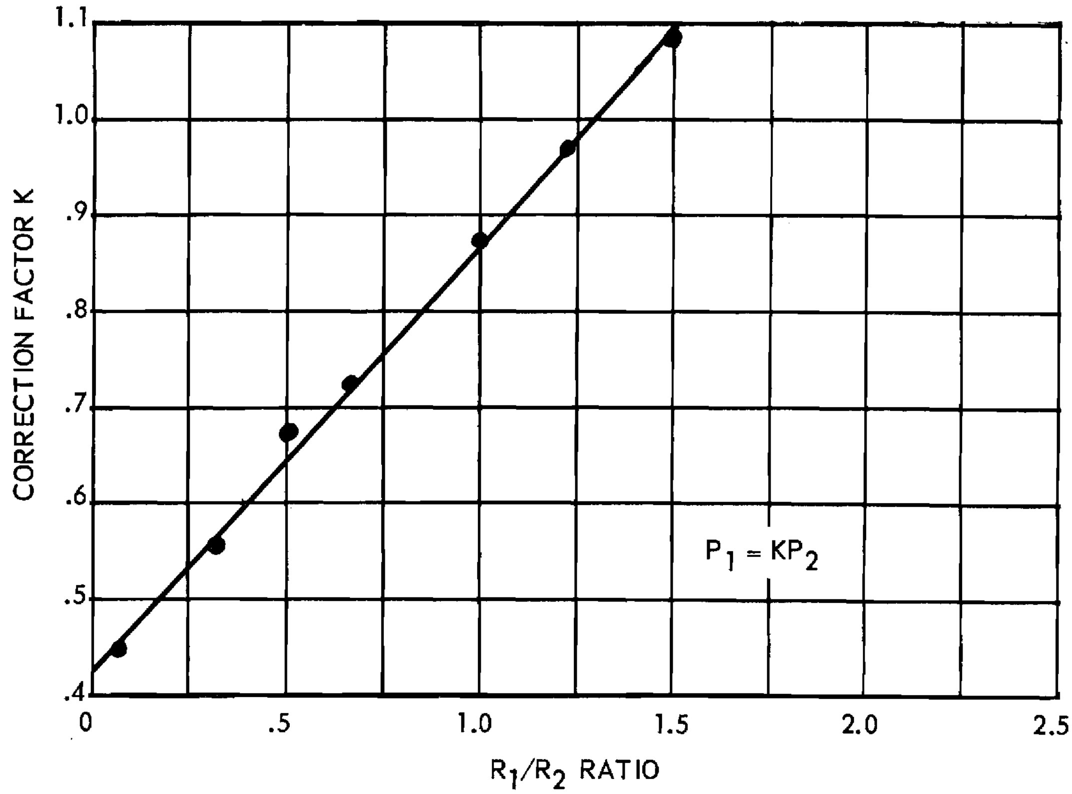


Figure 15. Calibration Curve for Various Rheostat Ratios.

Representative data obtained from these tests are listed in Table IV. The results indicate that the r-f measurements followed the same general trend as the d-c measurements, and different ratios of R_1/R_2 caused corresponding

TABLE III

EFFECT OF R_1/R_2 RATIO ON SYSTEM ERROR

$R_1 = R_2 = 50\Omega$				$R_1 = 50\Omega$, $R_2 = 100\Omega$			
Power in R_1 (mw)	Power in R_2 (mw)	System Error (%)	Normalized System Error (%)	Power in R_1 (mw)	Power in R_2 (mw)	System Error (%)	Normalized System Error (%)
0.45	0.37	- 19.0	+ 1.0	0.45	0.48	+ 8.0	- 2.0
0.80	0.65	- 19.0	+ 1.0	0.80	0.90	+ 12.0	+ 2.0
1.25	1.01	- 19.0	+ 1.0	1.25	1.44	+ 13.0	+ 3.0
1.80	1.51	- 16.0	+ 4.0	1.80	1.94	+ 8.0	- 2.0
2.45	1.95	- 21.5	- 1.5	2.45	2.70	+ 9.5	- 0.5
3.20	2.50	- 22.0	- 2.0	3.20	3.60	+ 11.0	+ 1.0
4.05	3.10	- 23.0	- 3.0	4.05	4.50	+ 11.0	+ 1.0

TABLE IV

R-F POWER MEASUREMENTS

$R_1 = R_2 = 50\Omega$				$R_1 = 50\Omega$, $R_2 = 100\Omega$			
Power in R_1 (mw)	Power in R_2 (mw)	System Error (%)	Normalized System Error (%)	Power in R_1 (mw)	Power in R_2 (mw)	System Error (%)	Normalized System Error (%)
0.45	0.39	- 13.0	0.0	0.45	0.53	+ 18.0	- 3.0
0.80	0.72	- 10.0	+ 3.0	0.80	0.97	+ 21.0	0.0
1.25	1.11	- 12.0	+ 1.0	1.25	1.52	+ 21.0	0.0
1.80	1.51	- 16.0	- 3.0	1.80	2.21	+ 23.0	+ 2.0
2.44	2.10	- 13.0	0.0	2.44	3.00	+ 23.0	+ 2.0
3.20	2.65	- 17.0	- 4.0	3.20	3.84	+ 20.0	- 1.0
4.06	3.52	- 13.5	- 0.5	4.06	4.90	+ 21.0	0.0

variations in the error of the system. In comparison checks between d-c and r-f measurements, it was noted that 10 percent more d-c power was necessary in R_2 to balance a given r-f power in R_1 than was necessary to balance an equivalent d-c power in R_1. However, the possibility exists that this error between r-f and d-c measurements is not a system error. Since no r-f standard is available at the present time, the r-f power applied to the Test Rheostat was calculated from the signal generator attenuator dial reading and an error of this magnitude could result from this calculation. It is planned to devote additional study to this possibility and an attempt will be made to determine the accuracy of the signal generator attenuator calibration.

Results from studies thus far indicate that a thermistor bridge power measuring system utilizing the principles incorporated in the experimental system should be capable of measuring r-f power in the range from 0.5 mw to 4.0 mw with an accuracy of $\pm$ 5 percent. Use of more accurately matched thermistors should allow the lower limit of the range to be extended below 0.5 mw. Although errors in the system due to thermistor bonding and poor heat conductivity of the resistive films are apparent, these errors are consistent and can be included in the system calibration.

C. Experimental CI Meter

1. Coaxial Crystal Parameter Bridge

Progress Report No. 2 discussed the impracticability of using commercial directional couplers in the construction of a coaxial crystal parameter bridge. This was primarily a result of the physical line lengths of the couplers which introduced undesirable impedance transforming effects. To overcome this difficulty a self-contained bridge was fabricated at Georgia Tech which utilized, in each arm of the bridge, a single directional coupler of the resistive loop type. This unit, which is pictured in Figure 16, allowed a considerable reduction in the physical line length of the bridge arms. In order to show the details of construction, one of the coupler units has been removed in the picture. The complete bridge is shown schematically in Figure 17. The variable capacitors C_{v1} and C_{v2} serve to balance the crystal holder capacitance. In order to allow either leg of the bridge to be used for the crystal and to physically and electrically maintain symmetry, an identical variable capacitor is used in each bridge arm. The difference signal is detected by the 1N416B diode and fed to a sensitive null indicator. L_1, L_2, C_1 and C_2 serve to filter the rectified signal voltage. The null indicator used is the Minneapolis-Honeywell Model 104W1G Electronik Null Indicator whose input impedance of 1000 ohms provides a load for the detector.

To initially balance the basic bridge assembly, three variables: the crystal-holder balancing capacitor, the coupler orientation or rotation and the coupler insertion must be properly adjusted in each bridge arm. Because of the interaction between the variables some difficulty was experienced in obtaining the desired degree of balance. However, the following procedure allowed a balance condition to be obtained that was considered adequate for initial tests with the bridge.

The crystal holder balancing capacitors were adjusted until equal impedances, as measured by the Hewlett-Packard Model 803A VHF Bridge were obtained at each crystal socket. Although not entirely independent of the loading and position of the coupler elements, the impedance reflected to the crystal socket

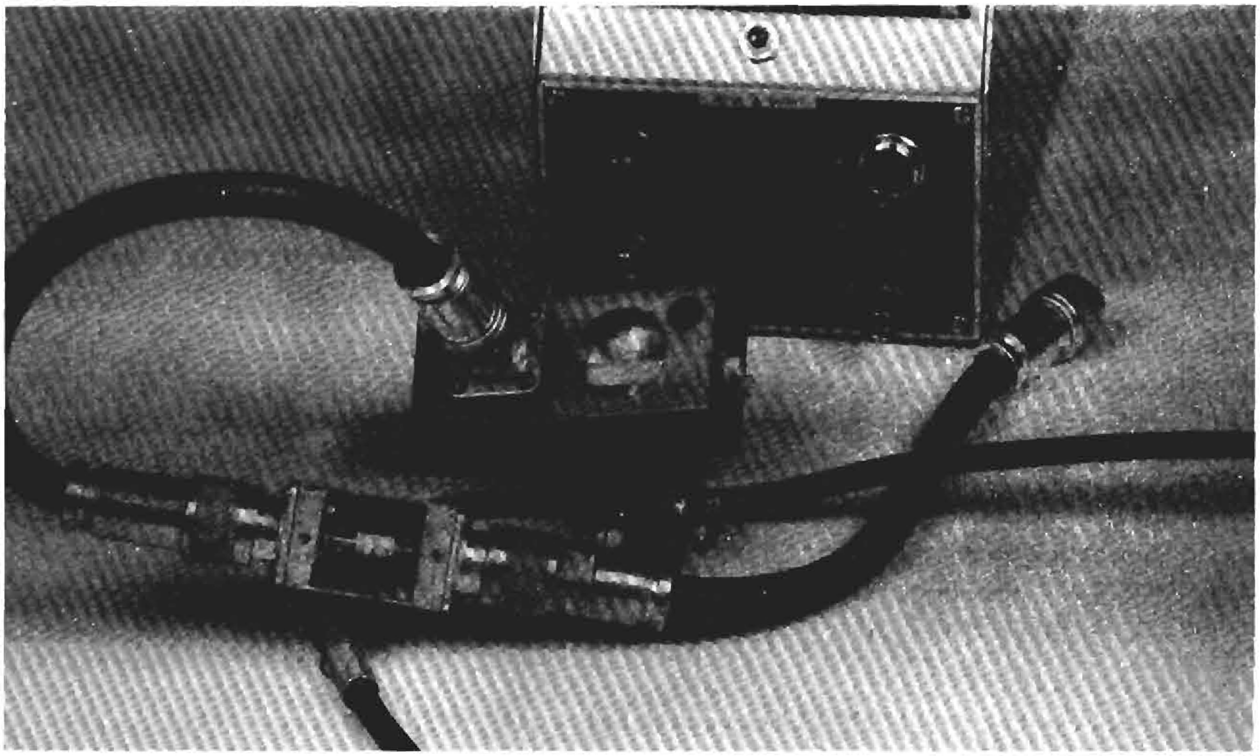


Figure 16. Coaxial Crystal Parameter Bridge.

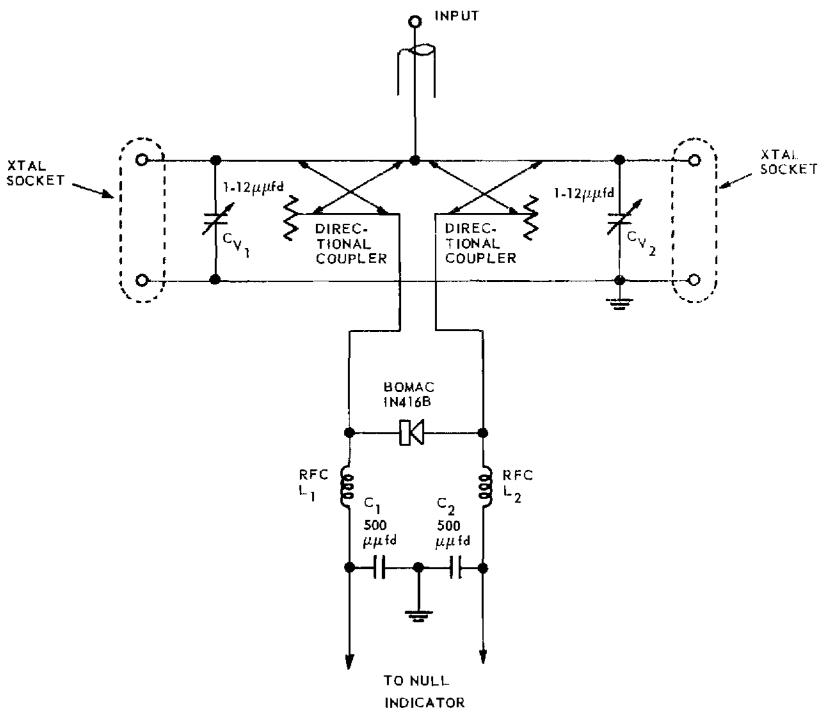


Figure 17. Schematic Diagram of Coaxial Crystal Parameter Bridge.

from these elements is below the sensitivity of the HP VHF Bridge. It was therefore possible to achieve an independent capacitive balance within at least the error of the HP VHF Bridge. Once the capacitors were balanced, the adjustment of the directional couplers was made by connecting the bridge to a signal source, and null indicator. The insertion and orientation of one of the couplers was adjusted for a maximum meter indication to insure balance at maximum sensitivity. The insertion and the orientation of the other coupler was then alternately adjusted for minimum null indications. Since the nulls obtained for insertion and for rotation converged rapidly it was only necessary to repeat the adjustment a few times to obtain a zero null indication and complete the initial balance of the bridge.

In order to determine the bridge accuracy several passive variable impedances were checked in the coaxial bridge. In each case a pair of identical impedances was used. One unit of each pair was set to some desired nominal value and was used as the reference impedance. The other unit was then adjusted for a null condition in the coaxial bridge. These two impedances were then measured in the HP VHF Bridge and the differences noted. The positions of the impedances in the coaxial bridge were then reversed and the operation repeated. The results of these measurements for a typical impedance at 200 and 300 mc/sec are shown in Table V. These results indicate that the impedances can be balanced in the coaxial bridge to better than 10 percent of the impedance value as measured in the HP VHF Bridge. Furthermore, the polarity of the errors obtained, when the impedance positions were reversed, indicates that the major portion of the error is due to the inherent unbalance remaining in the basic bridge assembly.

TABLE V

COAXIAL BRIDGE BALANCE MEASUREMENTS

Impedance	Freq.	Reference Position	Reference $Z\angle\phi$	Unknown Position	Unknown $Z\angle\phi$	Maximum Error Magnitude (Ohms)	Maximum Error Angle (Degrees)
Erie N500430 Variable Cap	300	1	$52\angle{-90}$	2	$50.5\angle{-90}$	- 1.5	0
"	300	2	$52\angle{-90}$	1	$54\angle{-90}$	+ 2	0
"	200	1	$104\angle{-90}$	2	$98\angle{-90}$	- 6	0
"	200	2	$104\angle{-90}$	1	$106\angle{-90}$	+ 2	0

The sensitivity of the bridge was checked in a similar manner using identical VHF Rheostats for the variable impedances. The reference Rheostat was set to the desired value and the unknown was adjusted for balance. The impedance values of the units at balance as measured by the HP VHF Bridge were recorded. The signal voltage to the bridge was adjusted to a particular drive level and the unknown impedance was decreased until a definite unbalance deflection of 1 mm was obtained on the null indicator. The impedance of the unknown was again measured and recorded. This procedure was repeated for an equivalent unbalance due to an increase in the unknown impedance. Typical results of these measurements are shown in Table VI. These results indicate that for drive levels greater than 0.5 mw and for null balance errors of 1 mm the unknown can be set equal to the reference Rheostat with an error in magnitude of less than 15 percent and an error in phase angle of less than 5 degrees. As illustrated by the table, considerably greater accuracy can be obtained for increased drive levels.

TABLE VI

COAXIAL BRIDGE SENSITIVITY MEASUREMENTS

Frequency (mc/sec)	Drive (mw)	Reference Impedance Z ($\Omega \angle \theta^\circ$)	ΔZ for 1-mm Deflection: ΔZ_1 (Ω/θ°)	ΔZ_2 (Ω/θ°)	Maximum Error: Magnitude (Percent)	Angle (Degrees)
250	.45	56/+10	48.5/+12	61/+8	13.5	2
250	3.6	56/+10	53 /+11	56/+9	5.4	1
250	.43	92/0	85 /+1	99/-3	7.6	3
250	4.0	92/0	89 /0	97/-2	5.4	2
250	.45	68/+5	62 /+7.5	75/+2	10.1	3
250	5.3	68/+5	65 /+6	72.5/+4	6.6	1
300	.48	60/+12	57 /+15	68/+8	13.3	4
300	5.0	60/+12	59 /+13	65/+10	8.4	2
200	.3	71/-5	62 /-3	80/-5	12.7	2
200	5.0	71/-5	67 /-3.5	73/-4	5.6	1.5

It should be noted that the drive levels recorded were obtained by measuring the signal voltage at the input to the bridge and calculating the power on the basis of measured impedance magnitude without regard to the small reactive component of the rheostat or to that contributed by the coaxial bridge itself. Nevertheless, the accuracy of the resulting drive levels are considered satisfactory for establishing the probable sensitivity of the bridge as designed.

Undoubtedly, some improvements in the bridge balance, accuracy and sensitivity can and will have to be made in a final or evaluation model. However, the results obtained are considered adequate for initially determining the suitability of using the bridge in conjunction with an active oscillator configuration.

2. Bridge-Oscillator Combination

Because of the natural division the development of the proposed CI Meter was pursued by separating the work into two convenient tasks: the development of a VHF crystal parameter bridge and the development of a VHF oscillator. As a result of this work the coaxial Crystal Parameter Bridge, as discussed in the preceding section, and the Plate Degenerative Oscillator, as discussed in Progress Report No. 2, were selected for testing in combination as a VHF CI Meter. The combination is effected by connecting the bridge unit, including the crystal under test, in place of the crystal alone in the Plate Degenerative Oscillator.

At balance the parallel arms of the bridge cause a capacity of approximately twice C_o to be presented to the oscillator. This increased capacity is "balanced out" at the plate of the grounded grid stage of the oscillator in the same manner that the crystal C_o alone was balanced in the oscillator without the bridge. In addition, the parallel combination of the VHF Rheostat and crystal at balance presents to the oscillator, at the crystal series resonant frequency, a net resistance equal to one-half of the series resonant resistance of the crystal.

Preliminary tests of the bridge-oscillator combination have not as yet yielded desirable results. One apparent and definite difficulty is the inability to properly track the oscillator over the desired tuning range. This is primarily a result of the inductive component contributed by the physical line lengths of the coaxial bridge unit. Although these lengths were reduced to the extent of avoiding serious impedance transforming effects they still are of sufficient length to modify the impedance presented to the oscillator. This effect can be counteracted simply at a given frequency by properly adjusting the C_o balancing capacity of the oscillator. However, it is very difficult to provide practical compensation such that tracking can be obtained over a suitable tuning range. Some improvement was obtained by utilizing a physical arrangement similar to the bridge at the plate of the oscillator grounded grid stage. This improvement was sufficient to allow limited tests on the oscillator and bridge combination over a narrow frequency range. In these tests crystal controlled oscillations were not maintained when the resistance of the VHF Rheostat was set near or equal to the crystal series resonant resistance.

The mechanism by which the Plate Degenerative Oscillator normally maintains crystal control may be the possible cause of the loss of crystal control when the VHF Rheostat is inserted in the bridge. As discussed in Progress Report No. 2, crystal controlled operation is achieved by the degradation or lowering of the plate impedance of the split-load amplifier by the crystal at resonance. Normally a considerable change in plate impedance is obtained between the crystal resonant and non-resonant conditions. In particular a plate impedance change by a factor of 10 or greater is obtained with a crystal having a series resonant resistance of 200 ohms. However, when the bridge and oscillator are used together with the VHF Rheostat set to the crystal series resonant resistance, the maximum magnitude change in the plate impedance that can occur between the crystal resonant and non-resonant conditions is 1 to 2. For example, if all reactive components are compensated and if a crystal having a series resonant resistance of 200 ohms is balanced by a VHF Rheostat set to 200 ohms then the maximum impedance presented to the plate of the split-load amplifier is 200 ohms and the minimum is 100 ohms. It is evident from the oscillator gain equations that this 1 to 2 impedance degradation is insufficient to maintain crystal controlled oscillations. The crystal phase slope near resonance is also degraded by the bridge but since the phase relationships in the oscillator are difficult to describe in the frequency range of 200 to 300 mc/sec the extent of this degradation is not readily determined.

Some additional tests are planned to more definitely establish the capability of this particular bridge-oscillator combination as a crystal impedance meter. However it appears that, although satisfactory within themselves, the Plate Degenerative Oscillator and the coaxial Crystal Parameter Bridge do not exhibit suitable characteristics when used in combination to permit the measurement of crystal parameters.

As is evidenced by the satisfactory operation of the lumped element Crystal Parameter Bridge at low frequencies, the crystal degradation caused by the bridge does not preclude crystal controlled operation in all oscillator configurations. It therefore appears advisable to further investigate various oscillator configurations that are more sensitive to the phase and impedance changes provided by the crystal and bridge.

V. CONCLUSIONS

A considerable number of crystal and resistive termination parameters have been measured to aid in determining the accuracy of the various instruments used in the crystal measurements standard. Some conclusions have been reached concerning the consistency of the data; however, the absolute accuracy of the measurements must remain questionable until accurately calibrated standards are made available. Specific conclusions are best enumerated as follows:

a. Providing certain precautions are taken the accuracy of crystal measurements is generally affected only slightly by the length of line used between the measuring instrument and the crystal.

b. The Marconi Type 1066/1 Signal Generator is generally sufficiently stable for crystal measurements over the frequency range from 100 to 300 mc/sec.

c. Power level measurements using thermistors in the GR type terminations have not been successful.

d. The practibility of making power measurements to the desired accuracy is still questionable.

e. Crystal drive level has very little effect on the parameters of some crystals, thus eliminating one of the variables when evaluating the other equipment.

f. It appears that a suitably sensitive null detector system can be constructed using the AN/APR-4 Type TN-17 tuning unit.

g. Impedance measurements of adequate consistency can be obtained when the HP Model 803A VHF Bridge is used with a suitably sensitive detector system.

h. Absolute accuracy of impedance measurements using the HP 803A Bridge is questionable.

i. Crystal measurements using the GR Admittance Meter have been found consistent over medium periods of time (several days).

j. No conclusive calibration checks have yet been made on the GR Admittance Meter since the terminations available are of the type which may have originally been used for factory calibration of the instrument.

Data obtained from the measurements made with the experimental thermistor bridge power measuring system indicate that a system of this type should be capable of measuring crystal power dissipations over the range of 0.5 to 4.0 mw, with an accuracy of $\pm$ 5 percent. Differences in thermistor bonding introduce an appreciable error; however, the error is constant for a particular pair of VHF Rheostats and may therefore be included in the system calibration. The poor heat conductivity of the resistive films of the VHF Rheostat causes an additional error to be introduced for rheostat resistance ratios other than unity. This error may be eliminated by maintaining the resistance ratio at unity or by utilizing a resistance ratio calibration curve.

The experimental model of the coaxial Crystal Parameter Bridge is capable in its present form of matching impedances with errors of less than 15 percent in magnitude and less than 5 degrees in phase angle at drive levels as low as 0.5 mw. Considerable improvement in accuracy may be obtained by increasing the bridge sensitivity but the accuracy presently obtained is sufficient for preliminary tests with active oscillators.

Initial tests of the coaxial bridge in combination with the Plate Degenerative Oscillator have not yielded the desired results. Proper tracking of the oscillator could be obtained only over narrow frequency ranges. In addition, when the bridge is adjusted near or to balance, crystal control of the oscillator is not maintained. The degradation by the bridge of the crystal phase and magnitude relations and the mechanism by which this particular oscillator normally maintains crystal control are apparently the primary causes of the loss of crystal control. Other oscillator configurations which are more sensitive to small phase and impedance changes may prove suitable for use with the bridge.

VI. PROGRAM FOR NEXT QUARTER

Work during the next quarter will be a continuation of that reported in the preceding pages with emphasis on the following objectives:

1. completion of the present measurements and analysis to determine the probable accuracy and sensitivity of the experimental thermistor-bridge power measuring system,

2. construction and test of a prototype crystal power measuring system to be used in checking crystal power in developmental crystal Parameter Bridges and in substitution type CI Meters,

3. completion of the experimental checks necessary to make a final determination of the feasibility of using the coaxial Crystal Parameter Bridge in conjunction with the Plate Degenerative Oscillator,

4. investigation of additional oscillator circuits for use with the coaxial Crystal Parameter Bridge,

5. further investigation of the possibility of using thermistors for measuring crystal drive level in the crystal measurements standard,

6. evaluation of the performance of the Marconi Type 1066/1 Signal Generator with line voltage and lead variations,

7. further investigation of sensitive null detector systems, and

8. continuation of the evaluation of the GR Admittance Meter and HP VHF Bridge for crystal impedance measurements.

Approved by:	Submitted by:
W. B. Wrigley, Head Communications Branch of the Physical Sciences Division	Douglas W. Robertson Project Director

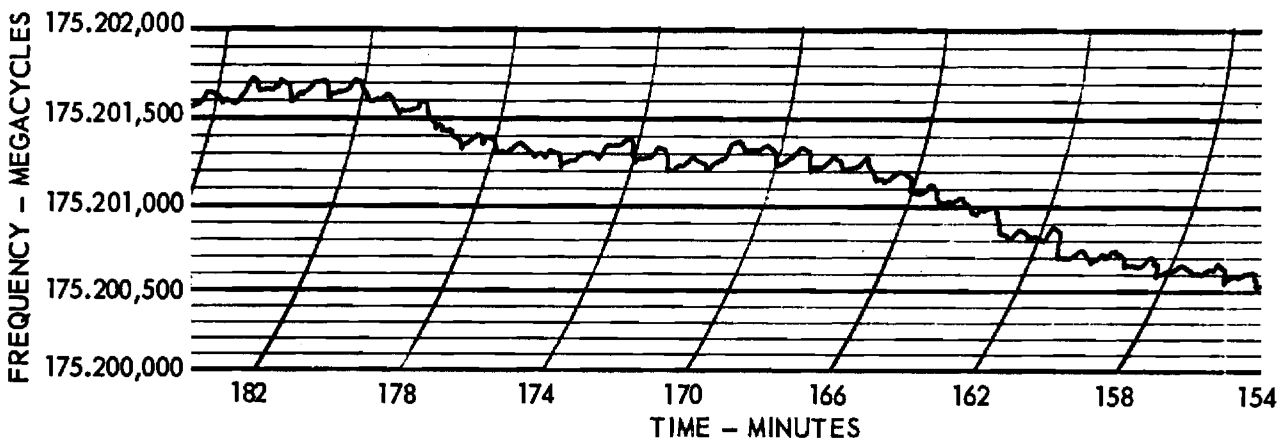
VII. PERSONNEL

Biographical sketches of the key technical personnel were included in Progress Reports No. 1 and 2. The time contributed by each during the present period is:

Douglas W. Robertson	Project Director	Full Time
Samuel N. Witt, Jr.	Research Engineer	2/3 Time
William R. Free	Asst. Research Engineer	Full Time
James E. Lane	Technical Assistant	1/3 Time

ADDENDUM

As indicated in Chapter IV, Section A3 of this report, the Marconi Type 1066/1 Signal Generator was partially evaluated by beating its output against a standard oscillator to obtain an audio frequency beat which was then recorded as shown in Figures 6-9. These data were obtained at the end of the period covered by this report. Since that time additional data have been recorded indicating that much of the short-term instability observed in Figures 6-9 was caused by the instability of the standard oscillator. The following recording was made by beating the Marconi against another standard oscillator known to have adequate stability. Thus it appears that the short-term frequency stability of the



Marconi is much better than reported in Chapter IV. Whether the long-term instability was caused by the Marconi or by the standard oscillator has not yet been determined. Conclusive evaluations should be available for the next progress report.

The following errors occurred in Progress Report No. 2 of this project and should be corrected as indicated.

1. The inequality signs in line 7 of page 16 should be reversed.

2. The last term in the denominator of equation 2 page 18 should read

$$R_k(R_{L_1} + R_{L_2} + 2r_p) \quad .$$

ENGINEERING EXPERIMENT STATION
of the Georgia Institute of Technology
Atlanta, Georgia

PROGRESS REPORT NO. 4

PROJECT NO. A-271

INVESTIGATION OF METHODS FOR MEASURING THE EQUIVALENT ELECTRICAL PARAMETERS OF QUARTZ CRYSTALS

By

DOUGLAS W. ROBERTSON, S. N. WITT, JR. and WILLIAM R. FREE

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CONTRACT NO. DA-36-039-sc-71191

DEPARTMENT OF THE ARMY PROJECT NO. 3-24-02-072
SIGNAL CORPS PROJECT NO. 867B

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16 JANUARY 1957 TO 1 JUNE 1957

PLACED BY THE U. S. ARMY
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ENGINEERING EXPERIMENT STATION
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TABLE OF CONTENTS

This report contains 66 pages.

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LIST OF APPENDIX FIGURES

LIST OF TABLES

I. PURPOSE

The purpose of this project is threefold:

1. To study and investigate methods and techniques for measuring the equivalent electrical parameters of quartz crystal units in the frequency range of 150 to 300 mc/s, including:

   (a) A means for directly measuring the power drive of a crystal unit,

   (b) A simple and practical means of cancelling the capacitance of the crystal unit, C_o, at the test frequency, and

   (c) A means of measuring the effective resistance of the crystal unit at the series resonant condition.

2. To accumulate data from the investigations of 1. above, with a view of utilizing the information for the development of a practical test method for the frequency range 150 to 300 mc/s which will make it possible to:

   (a) Subject the crystal to any selected drive level between the limits of 0.2 and 4.0 milliwatts,

   (b) Measure crystal resistance values between the limits of 20 and 200 ohms,

   (c) Attain an accuracy of resistance measurement of ± 5 ohms or ± 10 per cent, whichever is greater, and

   (d) Attain an accuracy of resonant frequency determination within ± 0.001 per cent of the series resonant frequency of the crystal unit.

3. To study and investigate means for establishing a laboratory measuring technique to be used as a standard for measuring the equivalent electrical parameters of quartz crystal units in the frequency range of 100 to 300 mc/sec.

II. ABSTRACT

Further investigations of the calibration of various commercially available instruments for use with the Laboratory Standard Crystal Measurements System were conducted. None of the particular instruments which were investigated were sufficiently accurate for one percent overall accuracy.

A developmental system was used to obtain several admittance circle diagrams for each of 15 high frequency crystals over the frequency range from 140 to 455 mc/sec. The data were compared with measurements from other sources.

Initial investigations of the equivalent circuits of high frequency crystals based on the data from the Measurements Standard indicated that the presently used equivalent circuit does not entirely account for the crystal's behavior. This investigation did not progress sufficiently to provide definite conclusions.

A prototype thermistor-bridge power meter for measuring the r-f power dissipated in VHF quartz crystals was constructed and tested. Comparative measurements indicated the unit to be capable of measuring r-f power from 0.5 to 4.0 mw with an accuracy of $\pm$ 5 percent.

Impedance measurements made with the Coaxial Crystal Parameter Bridge in a passive arrangement indicated the bridge accuracy to be comparable with that of other available methods.

An experimental UHF capacitance bridge oscillator was constructed that displayed characteristics suitable for use with the coaxial bridge. Crystal controlled oscillations as high as 420 mc/sec were obtained with a modified version of this oscillator.

III. CONFERENCES AND PUBLICATIONS

Mr. W. B. Wrigley, Mr. D. W. Robertson and Mr. S. N. Witt, Jr. attended a conference at USASEL on March 18, 1957. The technical status of this project and the future courses of action were discussed. The immediate objectives as outlined under Chapter VI, "Program for Next Quarter," were agreed upon.

A paper entitled "Quartz Crystals Above 200 Megacycles" was presented by Mr. S. N. Witt, Jr. at the Atlanta Section meeting of the Institute of Radio Engineers on April 26, 1957. A paper entitled "Crystal Measuring Techniques Above 200 Mc/sec" was presented by Mr. S. N. Witt, Jr. at the Eleventh Annual Frequency Control Symposium held in Asbury Park, New Jersey, on May 9, 1957.

IV. INTRODUCTION

This report actually covers an extended period of reduced activity for the 4-1/2-month period from 15 January 1957 to 1 June 1957. This extension, requested by USASEL, resulted from administrative delays in negotiating a 12-month extension of the present contract. It is expected that support for full effort will again be applied in July 1957.

V. EXPERIMENTAL WORK AND CIRCUIT STUDIES

A. Crystal Measurements Standard

1. Introduction

During this period, only a portion of the phases of development of the Crystal Measurements Standard were continued. The subsections previously titled "Stable Signal Generators," "Power Measurements," and "Detector Systems" are not included in this report since data previously reported indicated that the signal generator presently in use was satisfactory for immediate project needs and since further advancement in the study of power measurements and detector systems will require the purchase of various additional pieces of commercial equipment.

Principal efforts were directed toward investigations of calibration accuracies of various devices in current use. This study was greatly facilitated by the use of a large scale digital computer. The conclusion from this study is that the impedance and admittance bridges in current use do not provide sufficient accuracy to fulfill the purpose of the project. This, however, does not necessarily imply that the types of instruments involved are not satisfactory since the particular instruments which were used had been subjected to mistreatments of various kinds. Conclusions as to the potential accuracy of each instrument must await the purchase of new equipment.

Many crystal measurement runs were made on newly arrived crystals. Some of these measurements were compared with measurements obtained from other instruments. These measurements are, of course, subject to the calibration errors of the instruments used.

Some theoretical studies were made concerning the appropriate choice of equivalent electrical circuits for quartz crystals. These studies made use of laboratory measurements on various high frequency crystals. They were conducted primarily to determine the ability of the present measurements system to provide useful information about the quartz crystals.

2. Impedance Calibrations

Efforts to establish the sources and magnitudes of instrument errors were continued. In particular, large amounts of data were obtained on the Hewlett-Packard Model 803A VHF Bridge and the General Radio Type 1602-B Admittance Meter. These data consist of measurements made on General Radio 50-, 100-, and 200-ohm terminations which are assumed to be accurate to within one percent for impedance magnitude. Comparisons were made on the assumption that the impedance values of these terminations are exact.

A typical measurement setup is shown in Figure 1. The frequency calibration

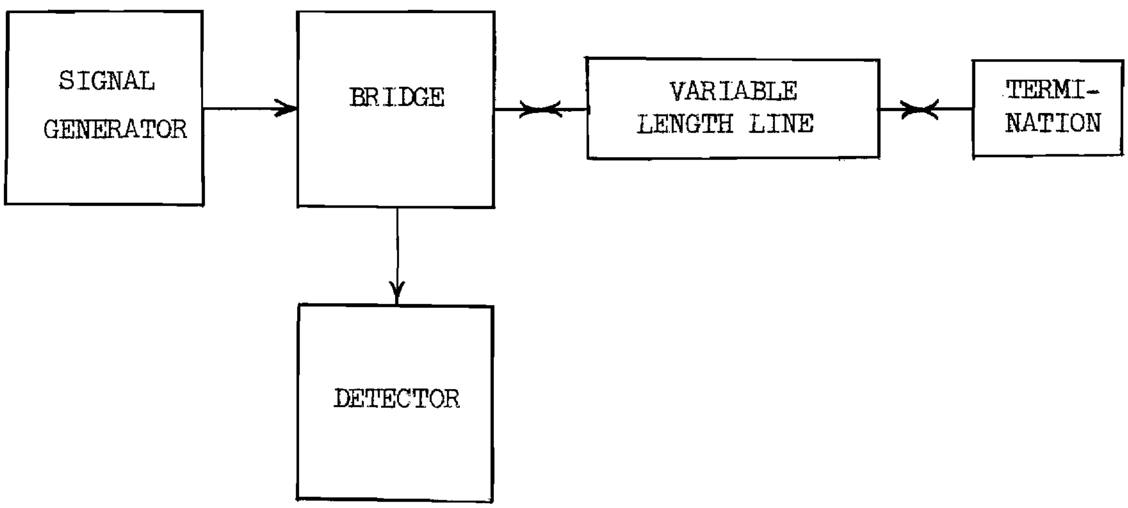

Figure 1. Impedance Calibration Measurement Setup.

of the Signal Generator was generally found to be satisfactory without the use of a frequency meter since no high-Q resonant elements are involved in the set-up. The Variable Length Line consisted of assorted combinations of fixed-length air-dielectric transmission lines (General Radio) and in some cases included a constant-impedance adjustable line. Amplitude modulation of the signal source was sometimes employed to obtain greater useable detector sensitivity. This was also possible because of the absence of high-Q resonant elements in the setup. General Radio Type 874 connectors with "Cliplocks" were used in making coaxial connections wherever possible. Care was taken to reduce direct signal leakage between instruments to a minimum by minimizing non-critical line lengths and employing solid coaxial cable wherever possible.

Sources of errors which were discussed in the previous progress report are:

a. human errors in reading the bridges,

b. errors caused by poor null indication,

c. drift in the bridge, terminations or other elements with time,

d. errors in calibration of the terminations,

e. errors inherent in the methods of applying corrections to the readings, and

f. errors in bridge calibration.

Item e was the first of these sources of errors that was more fully investigated during this report period. Since impedance measurements were made for arbitrary lengths of transmission line, it was necessary to make one or more short-circuit measurements and then subtract the short-circuit impedance from the readings obtained when using the termination. Of the various possible methods of subtraction, the one making use of Z-θ charts or Smith charts appeared to be most attractive because of the relatively small amount of time required. However, repetitive reduction of the same data yielded results differing by more than one percent in some cases. Mathematical subtraction of the short-circuit impedance using a slide rule was next attempted with a similar magnitude of disagreement resulting in the final impedance values. To obtain greater accuracy, a desk calculator and a set of mathematical tables were next employed. This combination was highly subject to human mistakes. The mistakes resulted primarily from the complexity of the computations. The equation which had to be solved was

$$Z_t = Z_o \frac{Z - Z_{sc}}{Z_o - \frac{Z_{sc} Z}{Z_o}}$$

where Z_t is the impedance of the termination to be calculated from a bridge reading,

Z_{sc} is the short-circuit bridge reading,

Z is the bridge reading with the termination in place, and

Z_o is the characteristic impedance of the transmission line.

Some of these quantities are complex impedances, thus adding to the difficulties already inherent in making the calculations.

Since satisfactory agreements were never obtained among the methods of short-circuit subtractions discussed above, the computations were performed on a Remington Rand ERA 1101 Univac Computer. Typical results obtained using the various computation methods are illustrated by Figure 2. It can be seen that the desk calculator calculations were sufficiently accurate, providing mistakes could be eliminated; however, this process was very time consuming, requiring

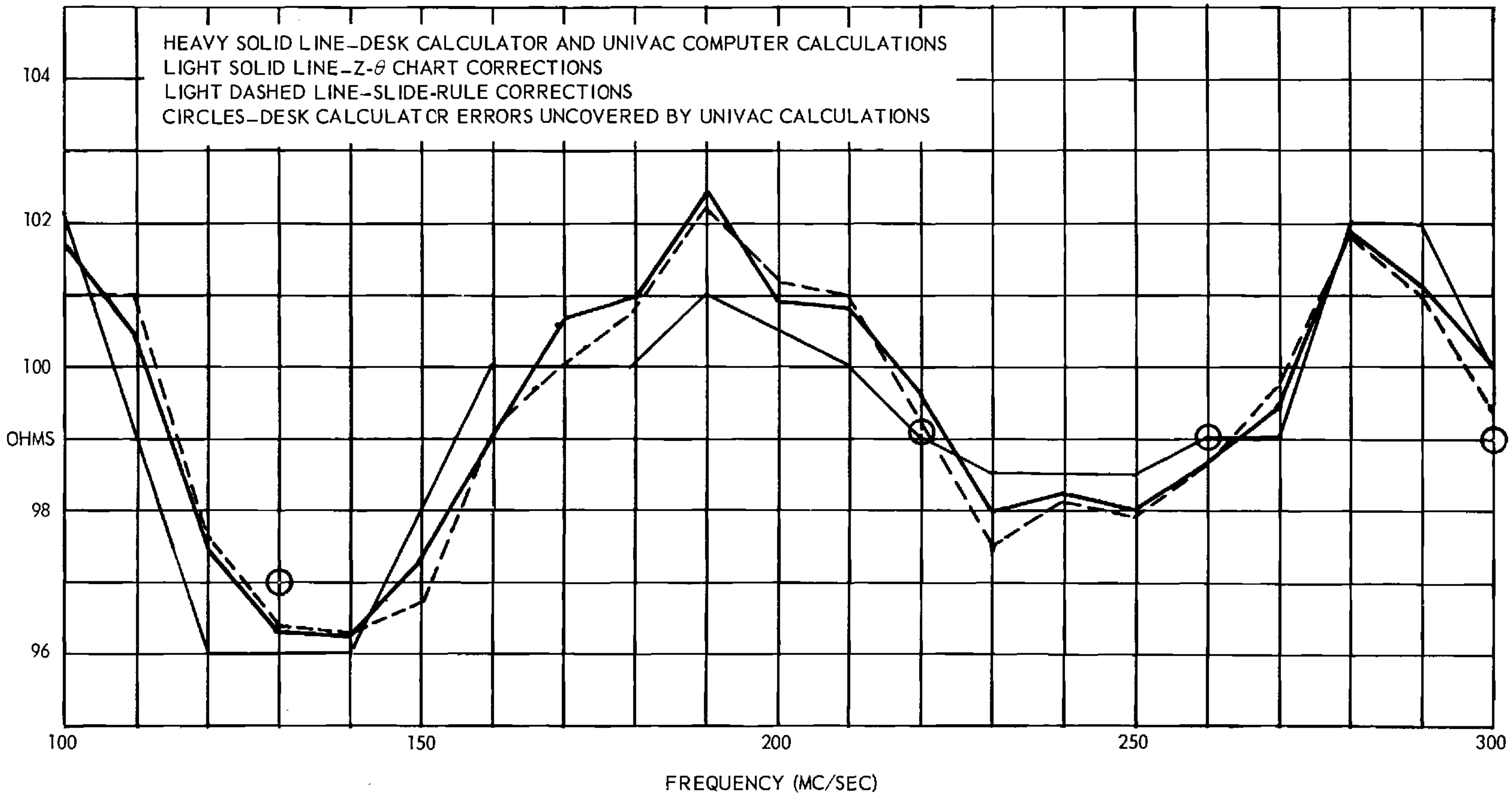

Figure 2. Comparison of Various Methods of Line Length Subtraction.

approximately 15 hours of time to subtract the short circuit for 20 points with the likelihood of appreciable errors remaining in 20 percent of the final solutions. The computer provided 0.01 percent accuracy with no mistakes in 43 seconds of computation time. Typical total computer time included 5 to 7 minutes program loading time plus 1 to 1.5 minutes per set of 20 readings for loading and computation. Fifteen to thirty minutes of personnel time were required for preparing the data for each set of 20 readings. The initial preparation of the computer program, however, required in excess of 20 hours of personnel time.

The use of the digital computer completely eliminated the errors inherent in the methods of applying corrections to the readings.

Figure 3 shows a graphical summary of the data obtained when using a particular HP Model 803A VHF Bridge to measure the impedance of a GR 100-ohm termination. Two of the curves show the data obtained by applying corrections for line length only. The third curve presents data which were fully corrected by applying the correction curves supplied with the bridge. These curves correspond to the curves of Figure 13 of Progress Report No. 3 except that the line length subtraction was performed by the computer for the current presentation. Some improvement in accuracy, especially for the phase angle, was obtained by the application of the correction curves provided with the bridge.

Figure 4 presents similar curves obtained by replacing the 100-ohm termination with a GR 200-ohm termination. An appreciable improvement in accuracy was obtained, in this example, by using the correction curves provided with the bridge. These curves correspond to Figure 14 of Progress Report No. 3.

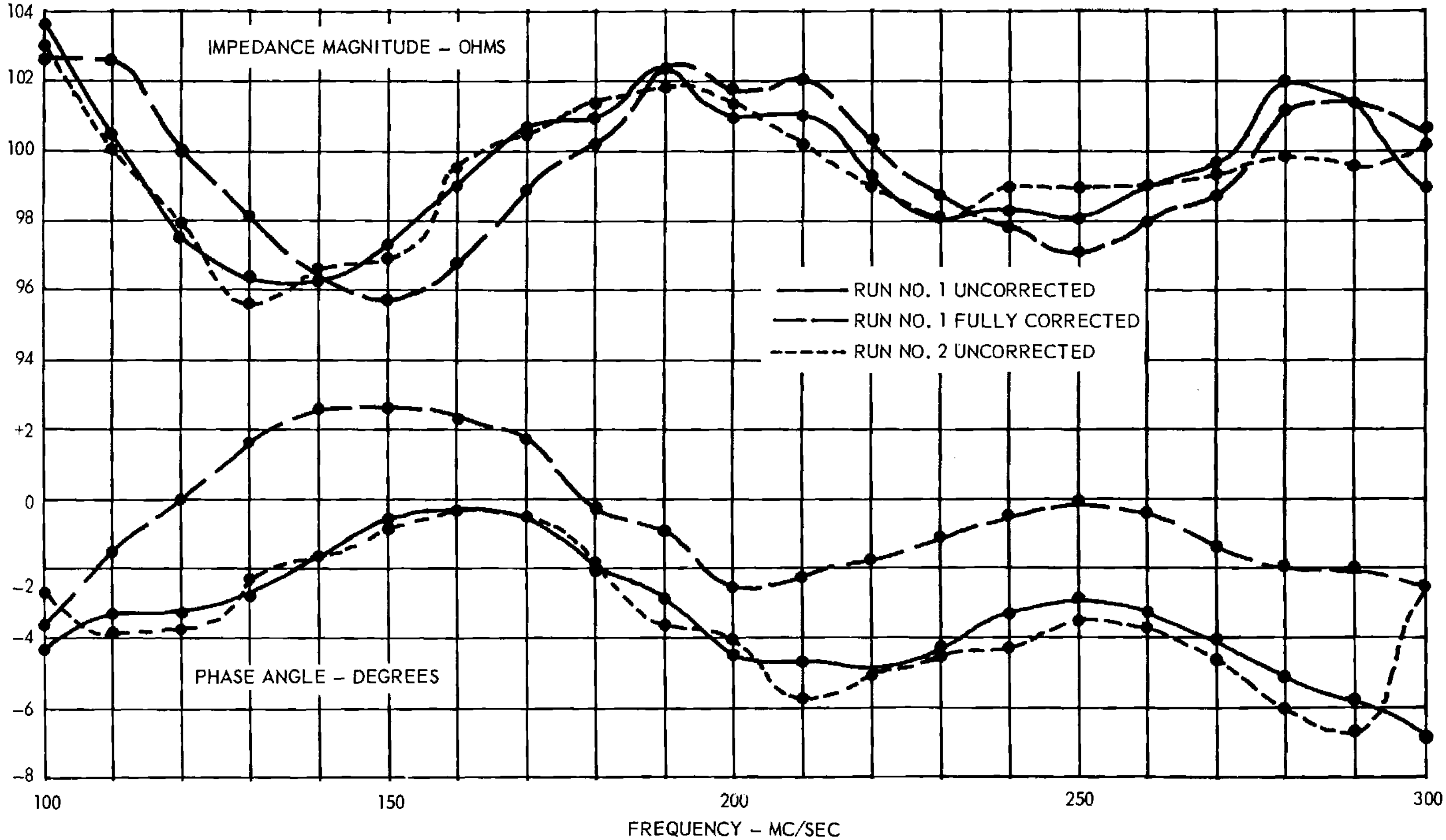

Figure 3. Bridge Measurements of 100-Ohm Termination.

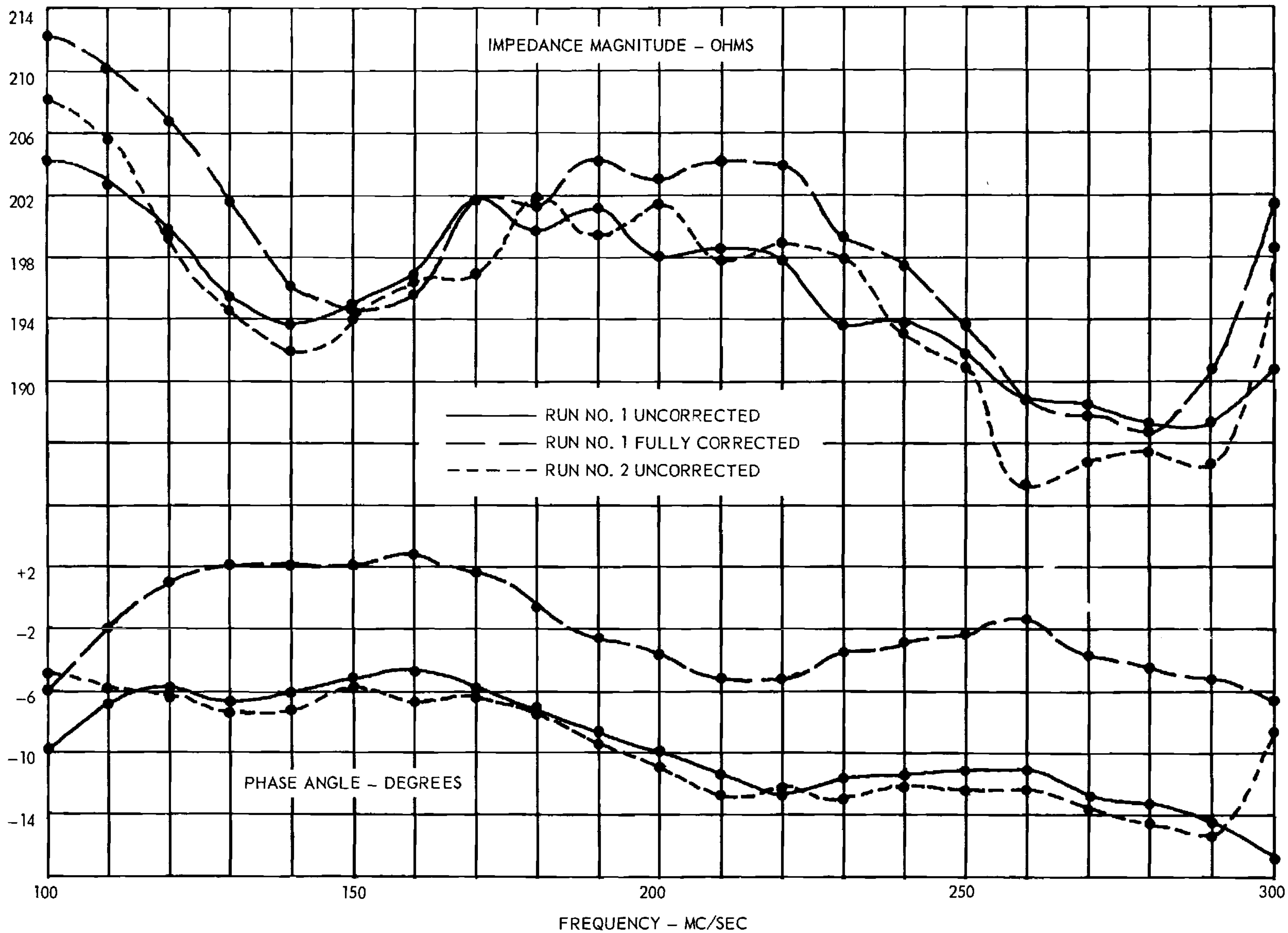

Figure 4. Bridge Measurements of 200-Ohm Termination.

Other data indicated that errors caused by poor null indication and errors due to drift were compartively small for the previously presented data. Errors due to poor null indication may, however, become appreciable when AM modulation of the signal source cannot be used. Thus the errors indicated in Figures 3 and 4 may be associated with (1) human errors in reading the bridge, (2) errors in calibration of the terminations, and (3) errors in bridge calibration. The first and third errors may be appropriately grouped as "bridge errors." If the errors in calibration of the terminations can be considered to be zero, the data presented in Figures 3 and 4 indicate that the particular VHF bridge can be specified to be accurate to within 7 percent for impedance magnitude and within $\pm$ 6 degrees for phase angle with full corrections applied and for the particular impedances and line lengths involved. Other data indicate that approximately the same accuracy can be obtained for any impedance with a magnitude between 50- and 200-ohms and for any line length except lengths which approach odd multiples of one-quarter wavelength. The accuracy may be specified to be 9.5 percent for impedance magnitude and $\pm$ 20 degrees for phase angle when the computer is not used for short-circuit subtractions and when the corrections supplied with the bridge are not applied.

Another HP Model 803A VHF Bridge was briefly investigated and was found to have slightly poorer accuracy. Both of these bridges had been in use for several years and had not always received the proper treatment. This model of bridge has been improved by the manufacturer in recent years; thus, current production models may show appreciable improvement in accuracy over the particular instruments which were available to the project. Tentative plans are being made to either have one of the old bridges rebuilt or to purchase a new instrument for similar evaluation.

The General Radio Type 1602-B Admittance Meter was also subjected to intensive laboratory investigations. Runs were made using 50-, 100-, and 200-ohm terminations separated from the instrument terminals by transmission line lengths of 0, 10, 20, 30, 40, and 50 cm. The computer program was modified to perform admittance subtractions based on short-circuit admittance readings. The difference in length of 0.6 cm between the short-circuit and the terminations was not included in the corrections; however, this distance would modify the results only slightly. If the instrument accuracy were greater, the correction for this distance would become more important. Figure 5 shows a graphical summary of the data obtained by using the 100-ohm termination. Near points where the line length approached one-quarter wavelength, large errors were to be expected. Disregarding these regions, however, the accuracy of the instrument can be specified in most cases to be within 15 percent for impedance magnitude. The curves show that the accuracy is generally greater for the shorter line lengths. For example, the maximum error in impedance magnitude for the 0-cm line length is 7.5 percent. The computer data gave phase angle accuracies within $\pm$ 15 degrees in most cases and a maximum error of 6 degrees for the 0-cm line length. This data is not presented graphically. Because of the large errors observed for the 100-ohm termination, it was felt that the use of the computer was not warranted for correcting the 50- and 200-ohm data. When the Admittance Meter is used with a half-wavelength line both magnitude and phase angle errors are greatly reduced (typically less than 5 percent magnitude error and less than $\pm$ 4 degrees phase angle error).

This particular Admittance Meter had been in use for several years and had received very rough treatment which probably accounts for much of the

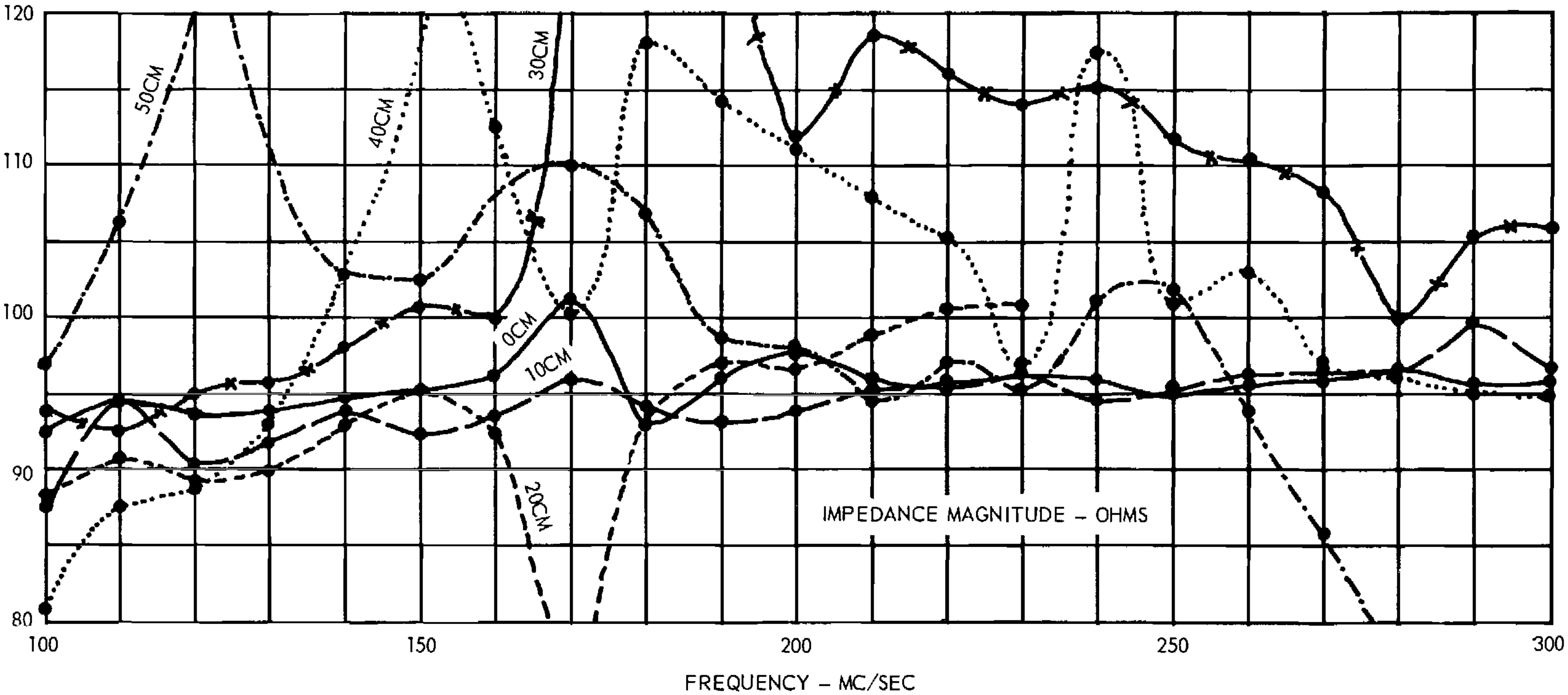

Figure 5. Admittance Meter Measurements of 100-Ohm Termination.

error. Tentative plans are also being made to obtain a new Admittance Meter for evaluation.

It was concluded that the instruments presently in use do not even approach the accuracy required to satisfy the purpose of the project. The data indicate, however, that new instruments, if given special care in calibration, may be capable of providing the necessary accuracy. The possibility of including calibration data for a particular instrument in the computer program has also been suggested. As applied to crystal measurements, this would mean that the data obtained from the VHF Bridge or Admittance Meter would be placed into the computer and the resulting output would be the fully corrected impedance characteristics.

3. Experimental Crystal Measurement Data

Experimental data were obtained on a series of 15 high frequency quartz crystals supplied by the USASEL. Complete circle diagrams were obtained for the principal response at each overtone frequency between the frequency limits of 140 and 455 mc/sec for each crystal. The setup used for obtaining the diagrams is shown in Figure 6. This setup is identical to that presented in Figure 2 of Progress Report No. 3. Although the previous section indicated that the VHF Bridge may at present be made more accurate than the Admittance Meter, the Admittance Meter was chosen for the crystal measurements because of its requirement of less null detection sensitivity. A half-wavelength line was used for each measurement to obtain greater accuracy and so that line length subtractions would not be required. In all, 76 circle diagrams were obtained for the 15 crystal units. This number does not include the many minor responses (spurious) which were also obtained.

The admittance characteristics of these crystals are shown in Figures A-1 through A-15 of the Appendix. Only the principal responses at each overtone are shown except for Figure A-15 where the frequency separations between the

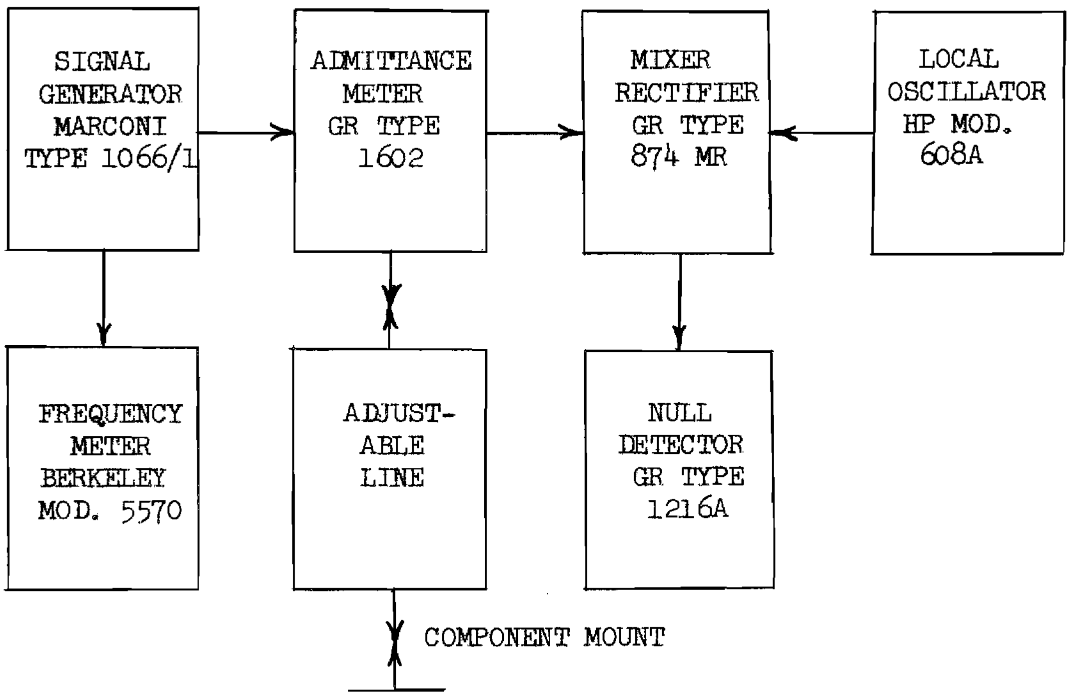

Figure 6. Present Laboratory Measurements Standard Setup.

principal responses and the spurious responses were very small. The numbers near each overtone response indicate respectively the overtone number and the approximate frequency of the response in mc/sec. The resonant frequency at each response is considered to be the frequency at the point of maximum conductance. This is the resonant frequency that would be obtained if cancellation coils were used to antiresonate the effective C_o of the crystal. The equivalent resistance is considered to be the reciprocal of the maximum conductance. The reader is cautioned, however, that this method of C_o cancellation does not necessarily yield the resonant frequency of the motional arm of the crystal. This aspect is discussed in the next section of this report.

Table I shows a comparison between the resonant resistance and frequency obtained from the curves of Figures A-1 to A-15 and the corresponding data supplied by USASEL as obtained by using a Crystal Impedance Meter. The values of

TABLE I

COMPARISON BETWEEN MEASUREMENTS OBTAINED WITH THE STANDARD SYSTEM AND MEASUREMENTS SUPPLIED BY USASEL.

	Standard Measurement System		Data from USASEL		
Crystal No.	Frequency (mc/sec)	Resistance (ohms)	Frequency (mc/sec)	Resistance (ohms)	C_o ($\mu\mu$fd)
Fa-57	144.997890	58	144.996591	60	7.1
Fa-59	144.995210	34	144.994504	38	6.6
Fa-89	154.969630	38	154.969724	38	5.8
Fa-91	155.025300	31	155.024304	32	5.8
Fa-92	154.983520	34	154.982208	35	5.8
Fa-103	165.010510	34	165.010252	36	6.4
Fa-104	164.965530	43	164.964807	42	6.0
Fa-105	164.950250	38	164.949722	37	5.9
Fa-116	175.029820	34	175.029814	36	4.8
Fa-117	174.899000	36	174.898072	33	5.7
Fa-118	174.896970	42	174.896575	39	5.8
Fa-82	188.944740	69	188.944609	70	6.1
Fa-83	188.996630	109	188.996369	102	4.4
Fa-40	195.979000	123	195.978463	106	6.0
Fa-44	196.013340	69	196.013830	63	8.1

C_o as obtained by USASEL are also included. The effective C_o as determined by the Measurements Standard may be readily calculated by considering the value of the susceptance at the point of maximum conductance.

The maximum disagreement between resistance values is 14 percent. With two exceptions, the values agree within 9 percent and for 8 measurements the agreement is within 5 percent. In all cases, the frequencies agree to within better than 0.001 percent. In 3 cases, the frequency agreement is better than 0.0001 percent. The resistance disagreements do not appear to be related to the frequency disagreements except for the Crystal No. Fa-40 where the disagreements are large for both frequency and resistance. It is possible that the characteristics of this crystal may have changed somewhat between intervening measurements.

4. Theoretical Crystal Studies

One of the 15 crystals whose admittance characteristics are presented in the Appendix was examined in greater detail to determine the validity of the conventionally assumed equivalent electrical circuit. These studies and conclusions, while necessary to determine the usefulness of the Crystal Measurements Standard, are nevertheless subject to errors introduced by the present limited accuracy of the system. The particular crystal chosen for these studies was Crystal No. Fa-116 whose circle diagrams are shown in Figure A-9 of the Appendix.

The holder characteristic of Crystal No. Fa-116 was first determined. This was accomplished by using the measurement setup of Figure 6 for the frequency range from 100 to 1000 mc/sec. The holder characteristic is plotted in Figure 7. The small circles represent the regions where crystal overtone

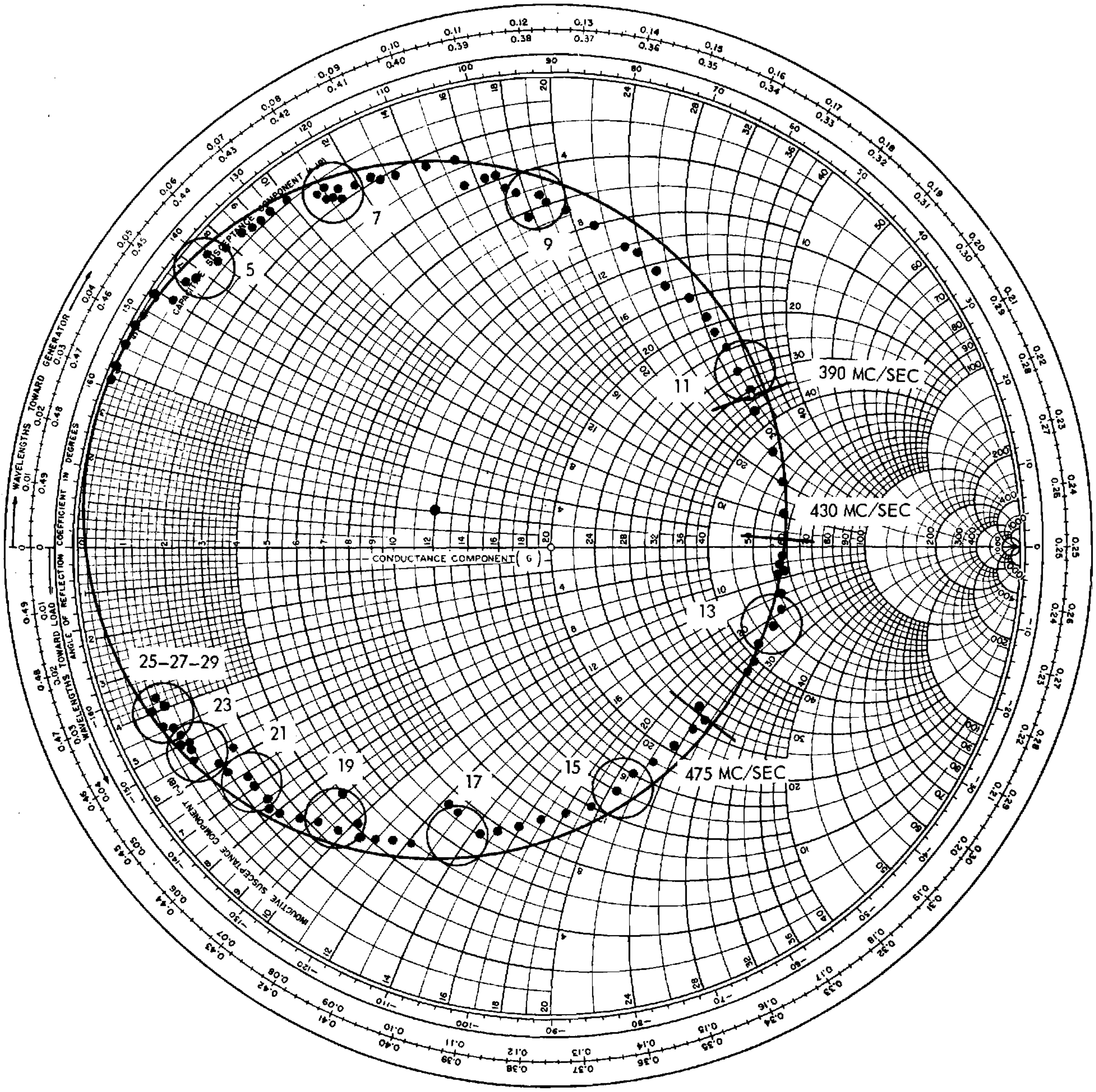

Figure 7. Crystal Holder Characteristics of Crystal No. Fa-116.

responses have a tendency to produce erroneous readings. The numbers near the small circles indicate the overtone number of the crystal response occurring in this region. The 21st through 29th overtone responses, all of which were appreciable and rather broad, made accurate readings difficult to obtain at frequencies above about 700 mc/sec. This situation was aggravated even more by the signal source instability at these frequencies (the crystal overtone responses at the higher frequencies have not been plotted due to this instability). The large circle in the figure was chosen as the circle which best represented the complete holder characteristic. It may be observed that this circle is not centered about the zero susceptance axis. This indicated the need for an additional shunt capacitance, C_o', as a part of the holder equivalent circuit which is shown in Figure 8. The element values appearing in Figure 8 are the values calculated from the half-power points on the circle diagram of Figure 7. The value of $(C_o + C_o')$ was also measured at 400 kc/sec and found to be 4.6 μμfd.

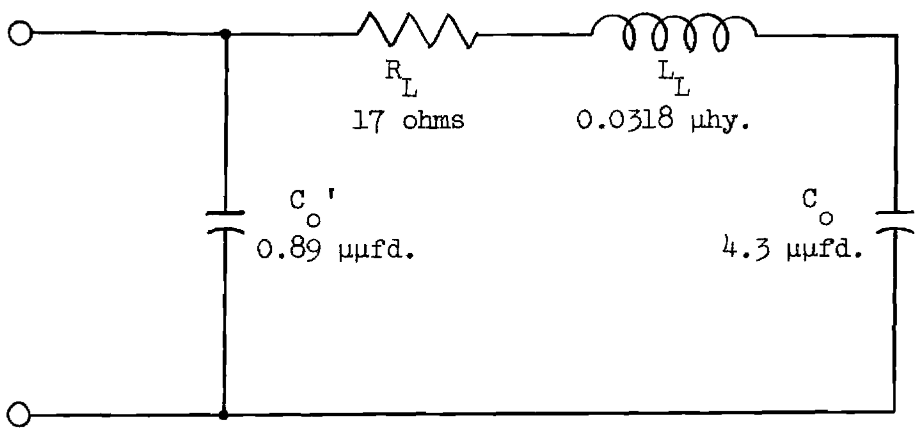

Figure 8. Holder Equivalent Circuit for Crystal No. Fa-116.

The fact that the measured points on the holder characteristic follow an elliptical path indicated a slight nonlinearity of element values with frequency. However, this nonlinearity appears to be negligible. The elliptical shape may, moreover, be due entirely to measurement errors.

The crystal response at 245 mc/sec was chosen for detailed study. The measured points and the resulting circle approximation are described by Figure 9. Figure 10 presents the corresponding rectangular plot of the measured points. The assumed equivalent circuit of the crystal is shown in Figure 11. The resonant frequency of the crystal's motional arm could not be readily determined from the curves of Figures 9 and 10; however, the circle diagram of the motional arm was obtained by successive subtraction of the holder elements using admittance and impedance Smith charts. The shunt element, C_o', was first removed by displacing the circle as shown in Figure 9. The circle was next transferred to an impedance Smith chart (not shown) where L_L and R_L were removed. The circle was then transferred back to Figure 9 where C_o was removed as indicated. As would be expected, the center of the circle fell very nearly on the conductive axis. This fact, however, does not by itself substantiate the correctness of the assumed equivalent circuit. Various frequency points must also be investigated. For example, if the motional arm circle of Figure 9 is correct, its resonance must lie at the point F_o. If this point is traced back to the complete crystal diagram by use of the Smith chart transformations, it will occupy the various positions indicated. If the point, F_o, is transferred to Figure 10, it will not occupy the anticipated position. Time was not available before the preparation of this report to determine whether or not this is the normal frequency shift accompanying an impedance transformation.

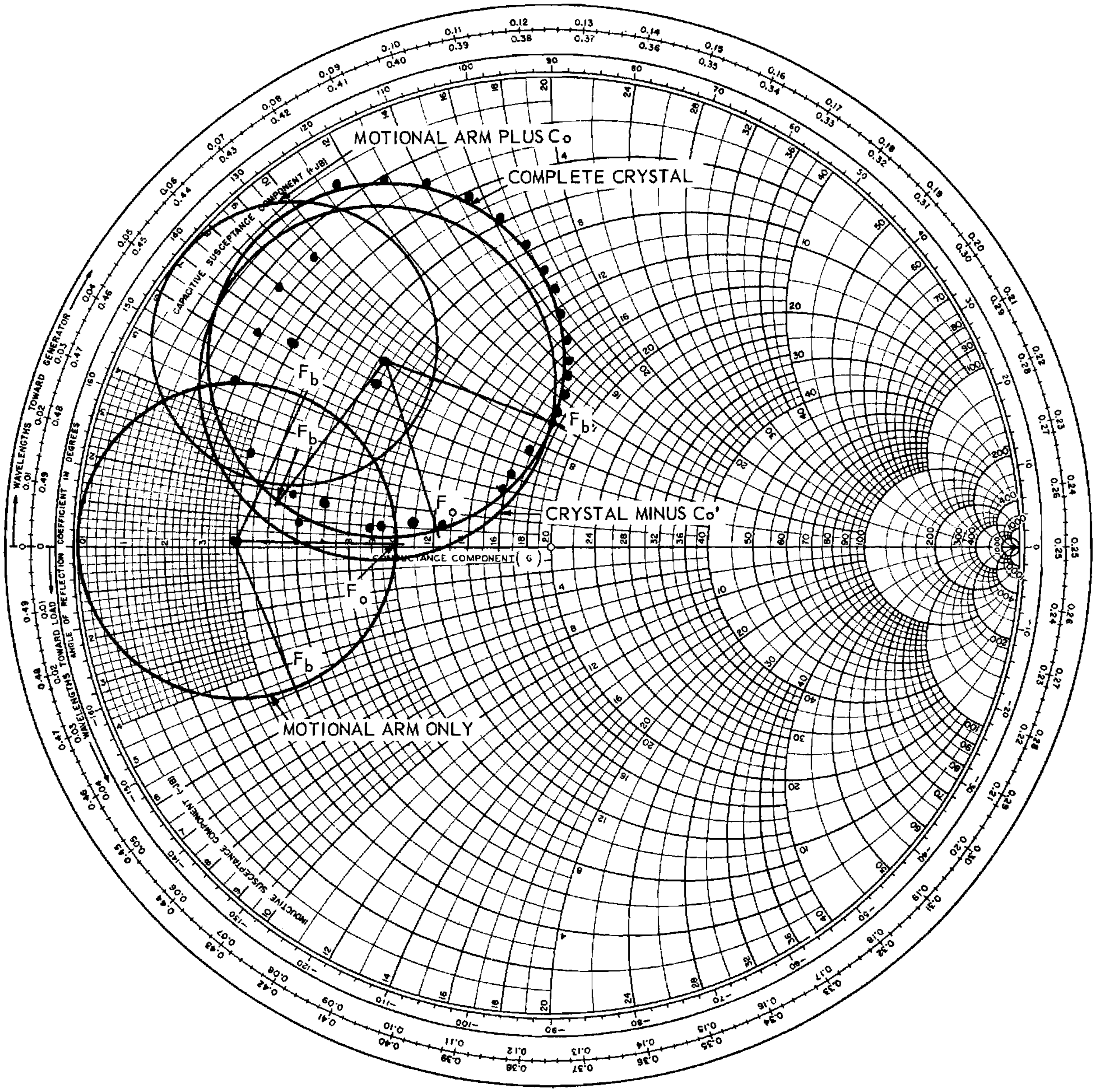

Figure 9. Characteristics of Crystal No. Fa-116 at 245 Mc/sec.

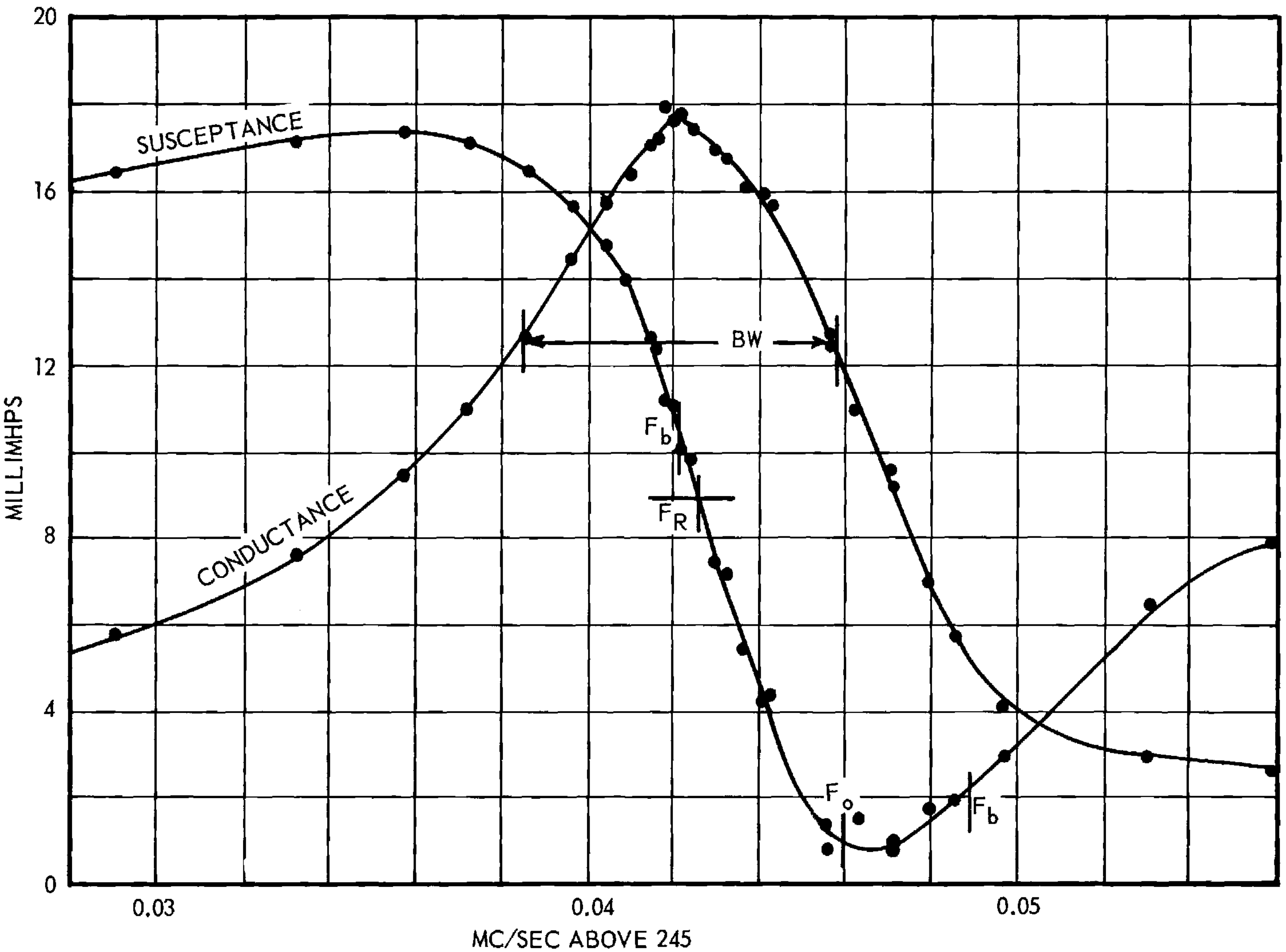

Figure 10. Rectangular Admittance Plot of Characteristics of Crystal No. Fa-116 at 245 Mc/sec.

If it is not, it is probable that the eventual explanation will result in the adoption of an alternate equivalent circuit.

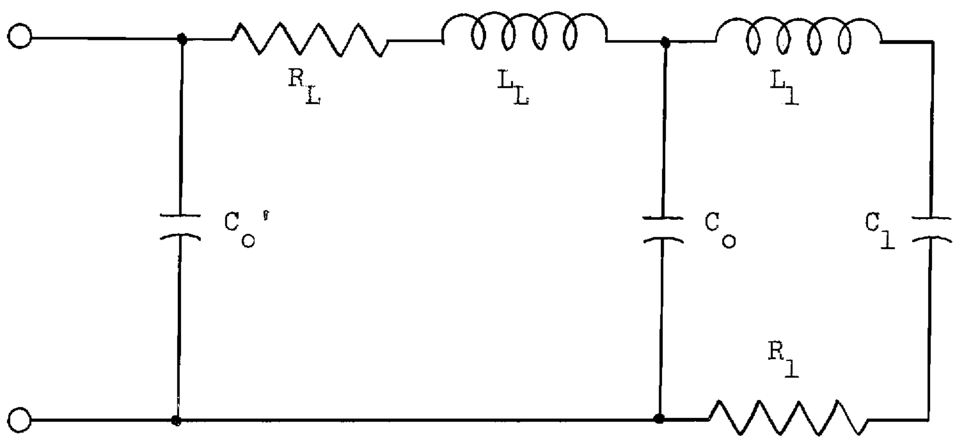

Figure 11. Assumed Equivalent Circuit of Crystal No. Fa-116 at 245 Mc/sec.

The element values for the equivalent circuit of the crystal's motional arm may also be determined by tracing the half-power bandwidth points, F_b, through the Smith charts to Figure 10, where the frequencies can be read from the curve. All natural and derived crystal parameters can then be calculated. For example, the Q_o of the motional arm was found to be 36,000. It is interesting to observe that the Q of the complete crystal unit with reactive cancellation may be calculated as 34,000 from Figure 10. It may also be observed from this figure that the most desirable reactive cancellation coil for this crystal unit would be one with a susceptance of 9 millimhos corresponding to an inductance of 0.07 μh. This corresponds to an assumed $(C_o + C_o')$ of 5.85 μμfd, which, results in a crystal resonant frequency of 245.0426 mc/sec compared to the resonant frequency of the motional arm of 245.0460 mc/sec. This raises the question as to which frequency should be the basis for the specification of the crystal's parameters.

Although the above development did not progress sufficiently to provide definite conclusions, it did indicate the need for further study of the equivalent circuit of quartz crystals at high frequencies. It is probable that additional investigations will offer satisfactory explanations for some of the observations which have been cited or that errors may be found which will invalidate the results presented.

B. Power Measurements

1. Introduction

The equivalent electrical parameters of quartz crystals are to a varying extent a function of the crystal power dissipation, and it is therefore necessary to measure and specify the power level at which the parameters are measured. A power measuring device which is compatible with the developmental parameter measuring instrumentation should exhibit the following characteristics: (1) sufficient sensitivity to measure r-f power in the range from 0.2 to 4.0 mw, (2) the ability to measure r-f power over the frequency range from 150 to 300 mc/sec, (3) the ability to measure power without any electrical connection between the dissipating body and the power measuring device, and (4) the ability to measure the power dissipation of the crystal without access to the interior of the hermetically sealed can of the crystal unit.

A thermistor bridge r-f power measuring system of the type shown in Figure 12 shows the most promise of satisfying the above requirements. Presently available thermistors and null indicators make possible a system which is capable of exhibiting a sensitivity in excess of that necessary to measure the power levels of interest. However, ambient temperature variations limit the degree to which this sensitivity can be practically utilized. The sensitivity of the system is limited by the maximum bridge unbalance indications which are caused by ambient temperature variations. These indications must be less than the allowable error of the minimum power level to be measured. The use of two thermistors in the bridge reduces the errors due to ambient temperature variations considerably, and makes possible the more effective utilization of the maximum sensitivity of the bridge.

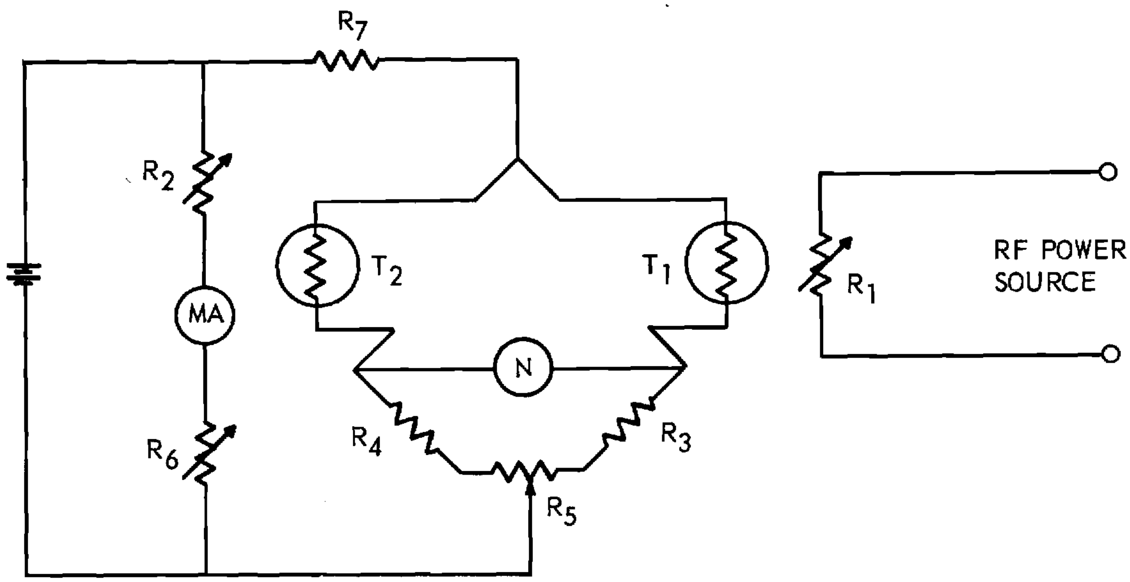

Figure 12. Thermistor Bridge Power Measuring System.

The two thermistors, shown as T_1 and T_2 on Figure 12, are mounted on the resistive elements of two rheostats, R_1 and R_2, and are connected as adjacent arms of a wheatstone bridge. The bridge is balanced by adjusting the bridge balance potentiometer, R_5. The r-f power to be measured is applied to Rheostat R_1, causing the temperature of the rheostat to increase. This temperature increase is coupled to thermistor T_1 and causes a decrease in the resistance of the thermistor. This decrease in the resistance of T_1 causes an unbalance in the bridge. Applying d-c power to the second rheostat, R_2, causes the temperature of R_2 and T_2 to increase which in turn decreases the resistance of T_2. When the decrease in the resistance of T_2 is equal to the decrease in resistance of T_1, the bridge will again be balanced. Under these conditions, the d-c power applied to R_2 will be equal to the r-f power applied to R_1, provided the two rheostat-thermistor combinations are identical. Any errors introduced by differences in the two combinations may be easily determined by applying a known d-c power to R_1 and adjusting the d-c power applied to R_2 until the bridge is balanced. Any difference between the known d-c power into R_1 and the d-c power applied to R_2 represents the error due to differences in the two rheostat-thermistor combinations. Therefore, this difference between the two d-c powers may be used as a correction factor for the total system error.

The procedure described above makes possible the measurement of r-f power dissipation in a rheostat without any electrical connection between the rheostat and the power measuring instrument, thereby eliminating any possibility of the power measuring instrument altering the operation of the system containing the dissipating body.

The quartz slab of a conventional crystal unit is encased in a hermetically sealed can and it is impractical to insert a heat sensing element into the can of each crystal unit to be measured. If R_1 is the rheostat of the Crystal Parameter Bridge or the test resistor used in the CI Meter substitution system, the r-f power dissipated in the rheostat will be equal to the r-f power dissipated in the crystal. Therefore, measurement of the power dissipated in the rheostat as described above, is equivalent to measurement of the power dissipated in the quartz crystal.

2. Prototype Power Meter

A prototype thermistor-bridge power meter for use in measuring the r-f power dissipated in VHF quartz crystals was constructed and tested. Figure 13 shows the prototype power meter connected to a Coaxial Crystal Parameter Bridge. A Minneapolis-Honeywell, Model 104WIG, Electronik Null Indicator is used as the null detector and a Marconi Type 1066/1 Signal Generator is shown connected as the r-f power source. A schematic diagram of the prototype power meter is shown in Figure 14. Two type 32CH1 Glennite Thermistors, shown as T_1 and T_2 on the schematic, were connected as adjacent arms of the bridge. The thermistors were bonded to the resistive films of two VHF Rheostats* so that the temperature of the resistive films determines the temperature and, hence, the resistance of the thermistors. This bond was made with Sauereisen High Temperature Cement No. P-7

* - - - -
Robertson, D.W., Scott, T.R. and Wrigley, W.B., Investigation of Methods for Measuring the Equivalent Electrical Parameters of Quartz Crystals. Final Report, Contract No. DA-36-039-sc-56730, Georgia Institute of Technology, Atlanta, May 31, 1956, 11-31.

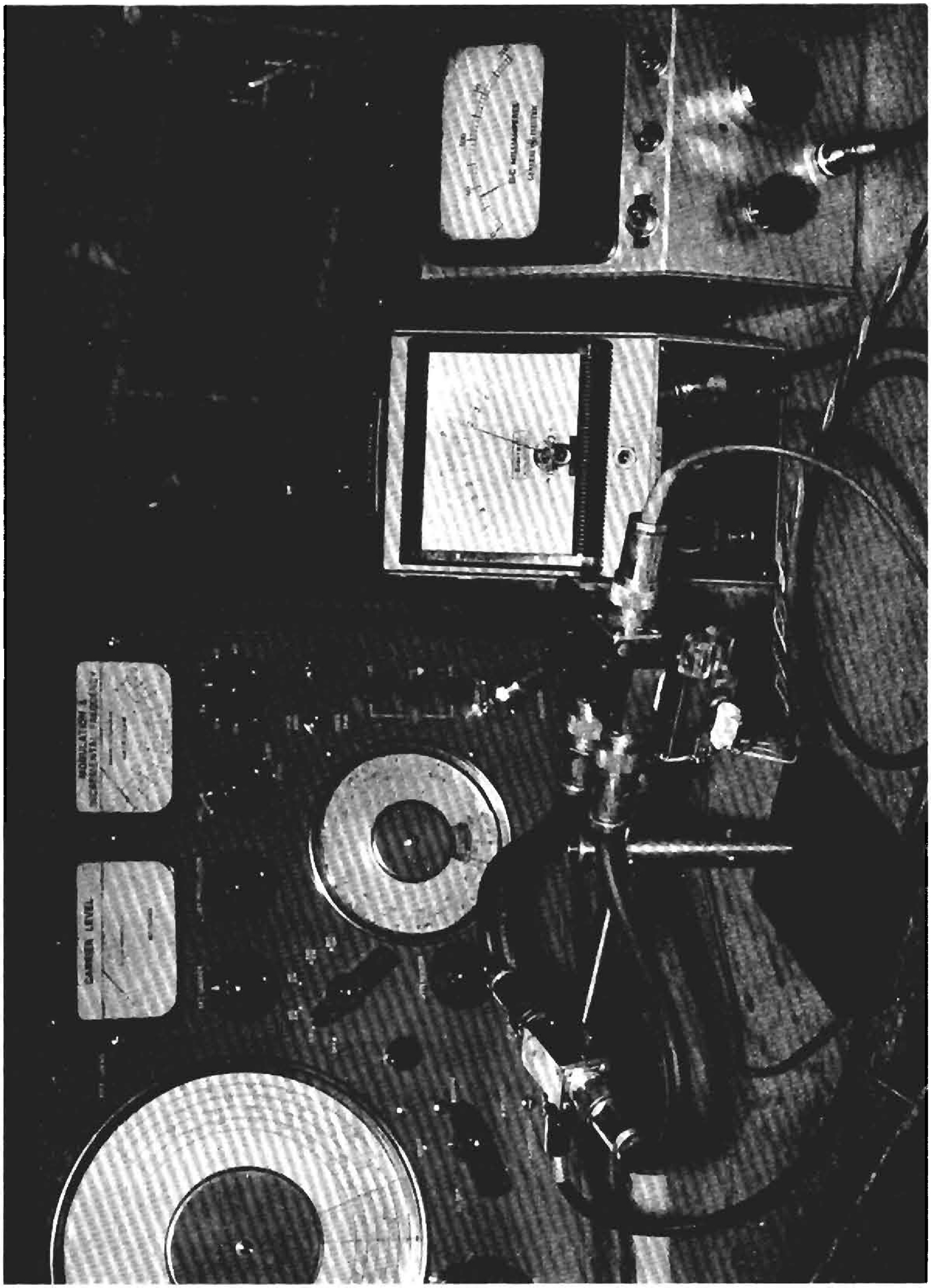

Figure 13. Prototype Power Meter.

which exhibits good heat conductivity and good electrical insulation. The test rheostat, shown as R_1 on the schematic, is normally operated as the bridge rheostat in the Crystal Parameter Bridge or as the test resistor in the CI Meter substitution system. If the resistance of the test rheostat is equal to the

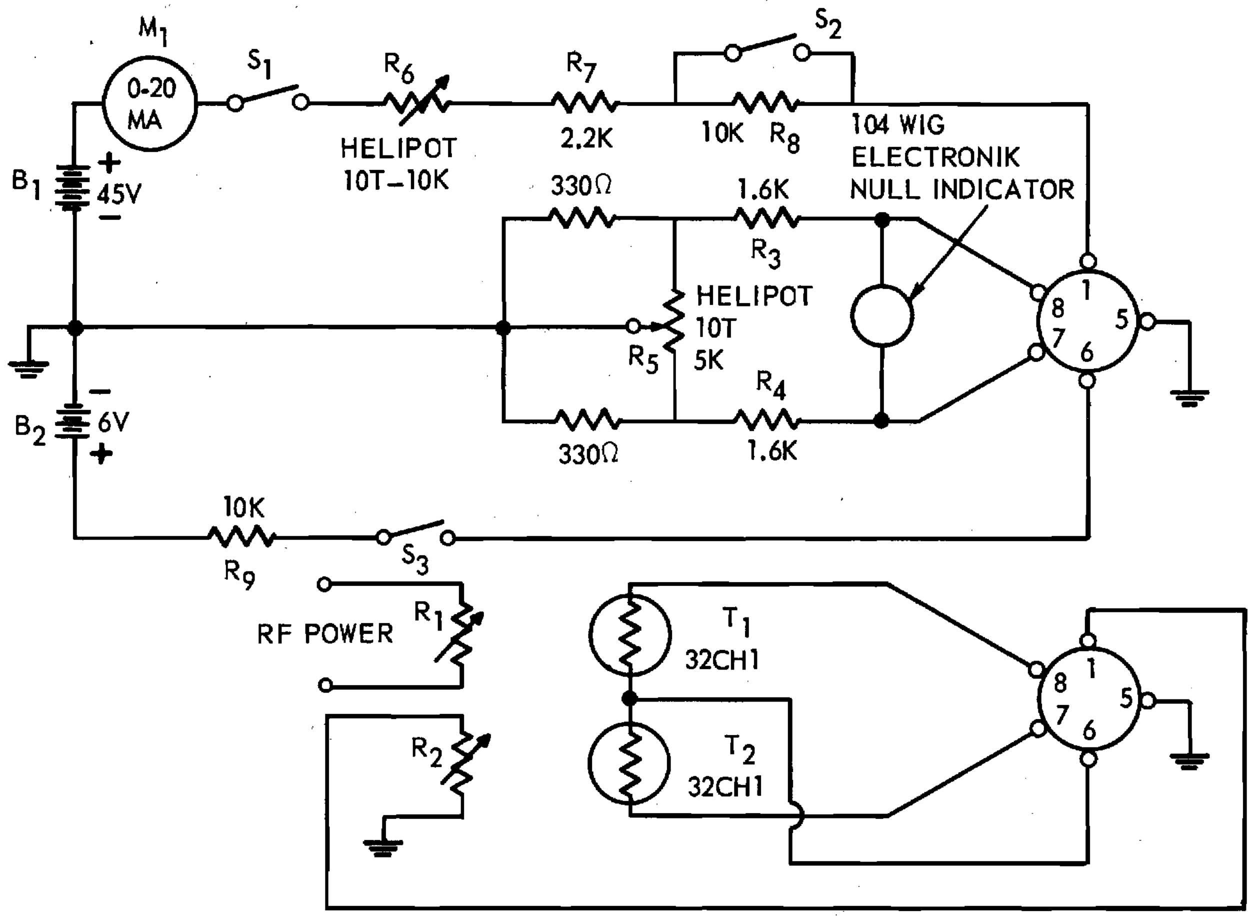

Figure 14. Prototype Power Meter Schematic.

series resonant resistance of the quartz crystal under test and if the frequency is equal to the series resonant frequency of the crystal, the power dissipated in the test rheostat is equal to the power dissipated in the crystal. The reference rheostat, R_2, is mechanically connected to R_1 to minimize ambient temperature variation effects. D-C power controlled by R_6 and metered by M_1 is dissipated in R_2.

The thermistor bridge is initially balanced with no power applied to the rheostats by adjusting R_5 with the bridge d-c power on. The r-f power to be measured is then applied to R_1. The heat generated in R_1 causes the resistance of thermistor T_1 to decrease, unbalancing the bridge. D-C reference power is then applied to R_2 and adjusted by R_6 until the bridge is again balanced. The d-c power necessary to obtain this balance is read on M_1. This reference power, when corrected for system errors is equivalent to the r-f power in R_1 and, hence, to the r-f power dissipated in the crystal.

3. R-F Power Measurements

In order to calibrate the power meter, specific amounts of d-c power ranging from 0.5 mw to 4.0 mw were applied to the test rheostat, R_1. The bridge was rebalanced by applying d-c reference power to the reference rheostat, R_2. The results are plotted as the d-c calibration curve of Figure 15. This curve represents the system error.

A Hewlett-Packard, Model 608C, VHF Signal Generator was used to apply specific amounts of r-f power, at 165 mc/sec, ranging from 0.5 mw to 4.0 mw, to R_1. The bridge was reblanced by applying d-c reference power to R_2. The curve obtained from these r-f power readings is also shown in Figure 15 for comparison with the d-c calibration curve. The r-f power applied to the test rheostat was calculated from the HP Signal Generator attenuator dial reading.

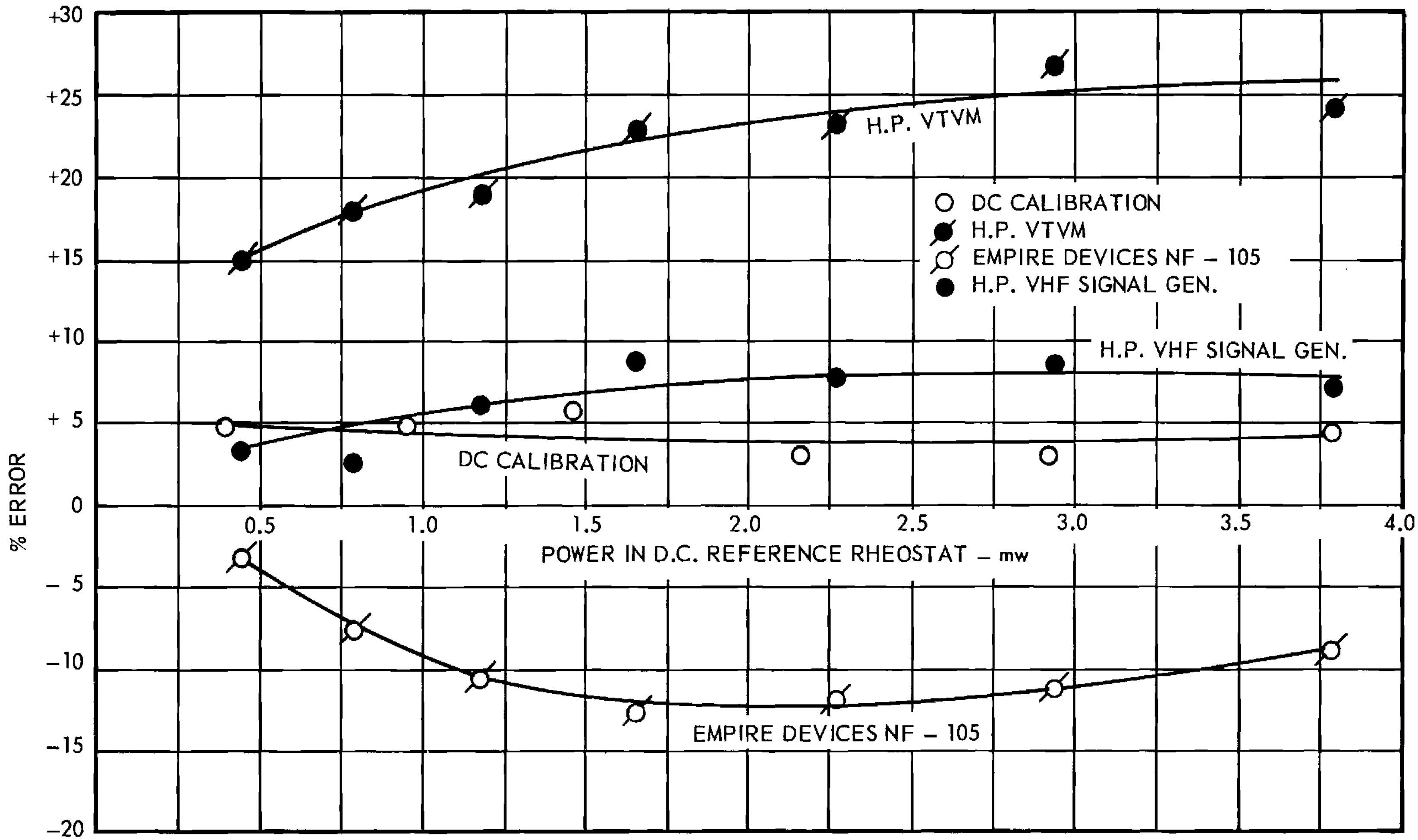

Figure 15. R-F Power Measurements.

In order to check the accuracy of the signal generator attenuator and as an additional check on the thermistor-bridge power meter, voltage measurements were made across the test rheostat with a Hewlett-Packard, Model 410B, Vacuum Tube Voltmeter and the signal generator output was measured with an Empire Devices, Model NF 105, Noise and Field Strength Meter. Results from these measurements are plotted on Figure 15 for comparison with the d-c power necessary in R_2 to balance the thermistor bridge. Figure 15 does not give a true indication of the accuracy of the instruments compared because the power values were calculated by squaring the voltage readings obtained from the instruments and, therefore, the errors shown on the power curves are approximately twice the errors of the instruments. Hence, all three curves are within the accuracy claimed for the instruments involved.

Since the curve obtained with the Hewlett-Packard VHF Signal Generator lies approximately midway between the curves obtained with the voltmeter and field strength meter, the r-f powers calculated from the signal generator attenuator dial readings were taken as correct values of r-f power. With this assumption, a comparison between the d-c calibration curve and the HP VHF Signal Generator curve indicated that the prototype R-F Power Meter should be capable of measuring r-f power in the range from 0.5 mw to 4.0 mw with an accuracy of $\pm$ 5 percent.

Several termination type commercial r-f power meters appear to be sufficiently accurate for use in checking the prototype power meter. An attempt is being made to procure one or more of these units in order to further evaluate the accuracy of the thermistor bridge.

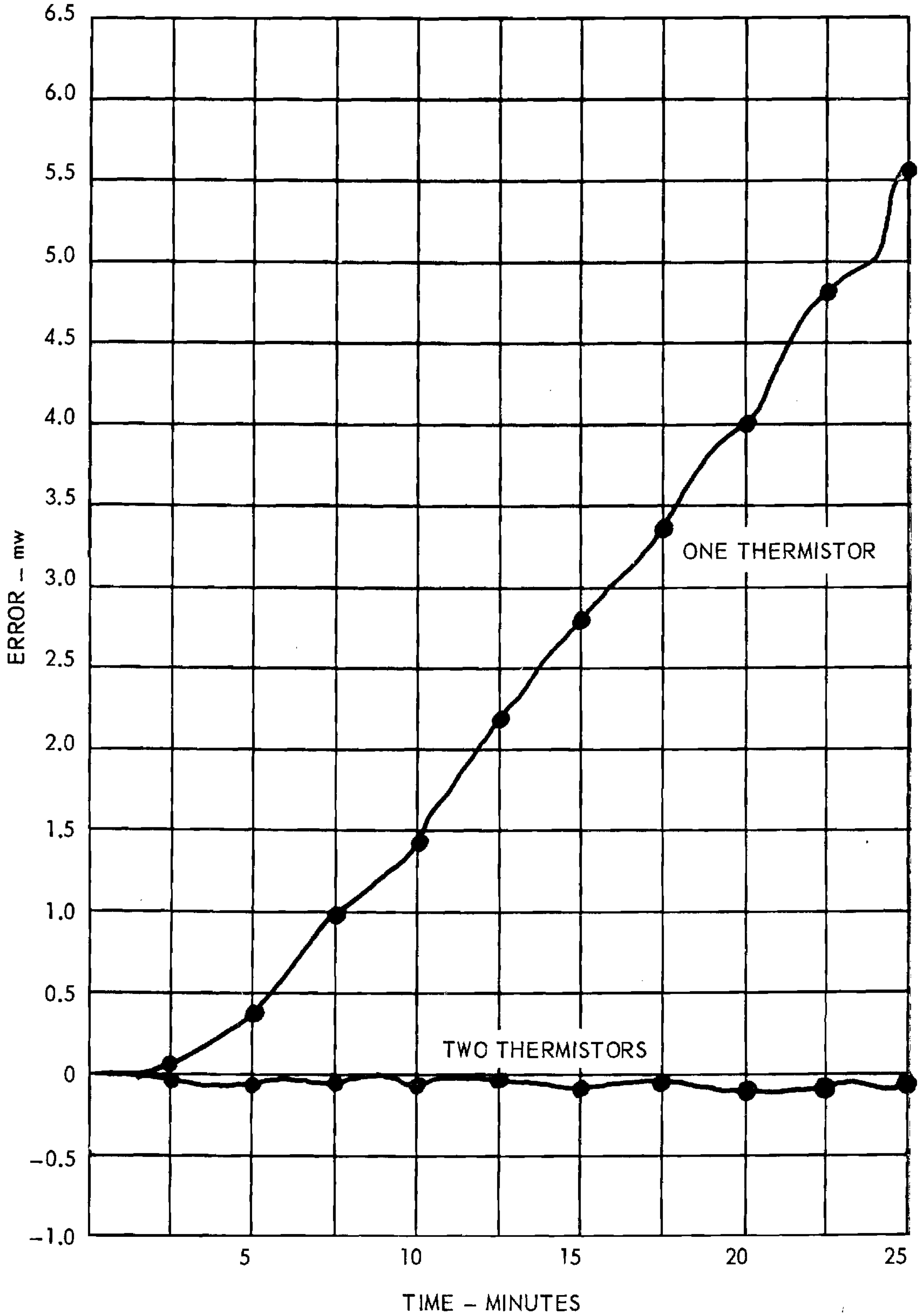

Figure 16. Ambient Temperature Variations of One and Two Thermistor Configurations.

In order to ascertain the improvement in useable bridge sensitivity obtained with two matched thermistors, tests were made over 30-minute periods with one-thermistor and two-thermistor bridge configurations. The results of these tests, as shown in Figure 16, indicated that the maximum error due to ambient temperature variations in the two-thermistor bridge was less than 2 percent of the error obtained with the one-thermistor bridge. Figure 17 shows the errors due to ambient temperature variations as a function of time in the two-thermistor bridge over a relatively long period of time. Assuming that a maximum period of 5 minutes is necessary to obtain a power reading, Figure 17

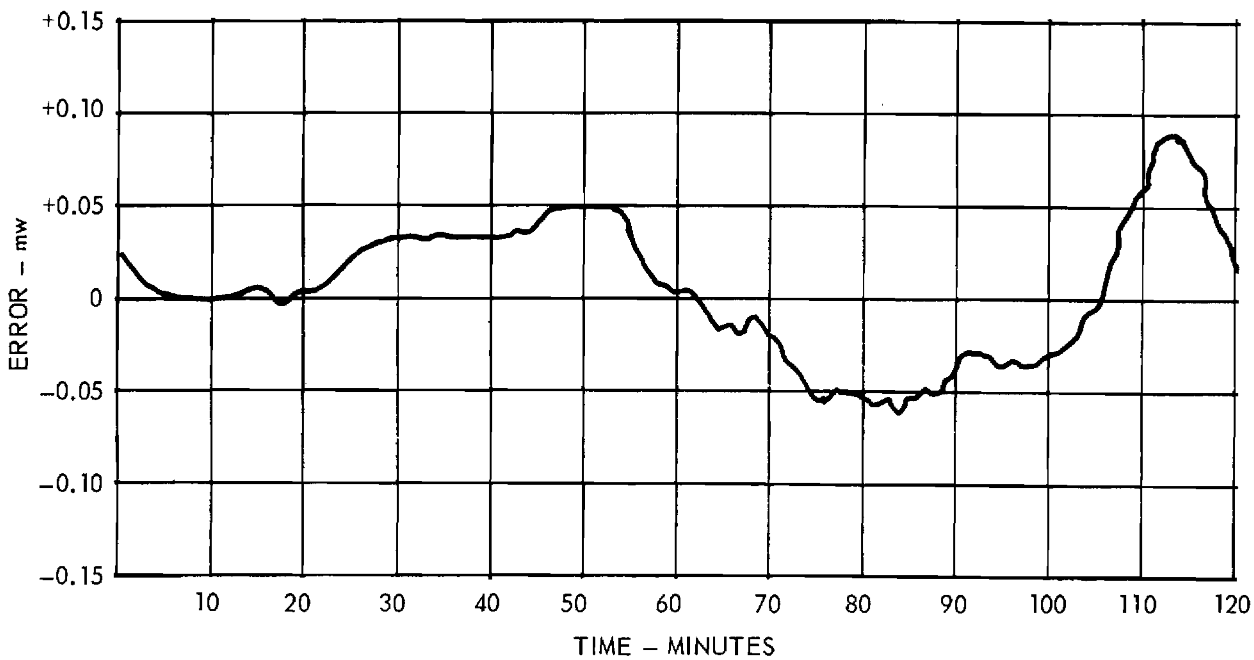

Figure 17. Ambient Temperature Variations of Prototype Bridge.

indicates that a maximum error of approximately 0.1 mw is possible. However, data from actual power measurements indicated that power levels as low as 0.5 mw could be consistently measured with an accuracy of $\pm$ 5 percent. The greater accuracy of the experimental readings was due to the improbability of the reading being taken at times when the temperature variations were maximum and to the fact that the time necessary to make the measurement was less than 5 minutes.

It is not possible, at the present time, to measure r-f power at a 0.2-mw level with the desired accuracy because the error due to ambient temperature variations is equivalent to a relatively large percentage of the r-f power being measured. Better matching of the two thermistors would reduce the deflections due to temperature variations and would permit lower values of r-f power to be measured with the desired accuracy. Improvement in the bonding between thermistor and dissipating body would result in a given ambient temperature deflection representing a smaller percentage of the power being measured and would also allow lower level r-f power to be measured accurately.

C. Experimental CI Meter

1. Coaxial Crystal Parameter Bridge

Progress Report No. 3 presented the results of passive measurements made on the Coaxial Crystal Parameter Bridge. These results indicated that the bridge in its present form was capable of matching impedances with errors of less than 15 percent in magnitude and less than 5 degrees in phase angle at drive levels as low as 0.5 mv. Considerably greater accuracy (5 percent and 2 degrees) was obtained by increasing the drive level or can be realized by increasing the sensitivity of the coupler elements. However, no effort was made to increase the sensitivity since the accuracy presently obtained is adequate to determine the usefulness of the bridge arrangement.

Additional checks were made on the bridge by utilizing it in a passive measurement setup to measure the series resonant frequency and resistance of a number of crystal units furnished by USASEL. The resulting bridge measurements were compared with those obtained by USASEL and with those obtained at Georgia Tech with the present crystal measurement standard.

Figure 13 shows a picture of the passive system used. The Marconi 1066/1 Signal Generator which was used as the external signal source exhibited a short time stability that was more than adequate to permit proper bridge nulls to be obtained. The thermistor power meter, also shown in Figure 13, was not used to measure crystal drive because of the unavailability of VHF Rheostat-Thermistor units covering the entire frequency range of the group of crystals. However, the crystal drive was set at approximately 2 mw for each measurement by measuring the voltage across substitution resistors (approximately equal to R_1) placed in each side of the coaxial bridge.

Table II compares the results of the bridge measurements with those obtained at USASEL and with those obtained with the Georgia Tech Crystal Measurements Standard. In each case a frequency difference of less than 0.001 percent, (target accuracy) was obtained between the bridge measurement and either of the two methods used for comparison. The average deviation appears to be approximately 0.0003 percent from the Measurements Standard and 0.0004 percent from the USASEL measurements.

Although resistance deviations greater than the desired accuracy of $\pm$ 5 ohms or 10 percent were obtained in four cases, these differences did not exceed 15 percent. With two of these crystals, No. Fa-40 and Fa-44, the differences occurred only between the coaxial bridge and the Measurements Standard results.

With the other two crystals, No. Fa-57 and Fa-82, the coaxial bridge measurement differed from both the Measurements Standard and the USASEL results. However, caution should be exercised in the resistance comparisons since information was not available as to the conditions under which the USASEL resistance measurements were made and since the coaxial bridge results were obtained by measuring the VHF Rheostat resistances with a conventional ohm meter without regard to phase angle considerations.

TABLE II

COAXIAL CRYSTAL PARAMETER BRIDGE MEASUREMENTS

	Coaxial Bridge		Measurements Stand.		USASEL	
Crystal No.	Frequency (mc/sec)	R_1 (ohms)	Δf (percent)	ΔR_1 (ohms)	Δf (percent)	ΔR_1 (ohms)
Fa-57	144.99760	52	+ .00020	+ 6	- .00068	+ 8
Fa-59	144.99511	33	+ .00007	+ 1	- .00040	+ 5
Fa-89	154.97008	36	- .00029	+ 2	+ .00023	+ 2
Fa-91	155.02535	30	- .00003	+ 1	- .00068	+ 2
Fa-92	154.98305	31	+ .00030	+ 3	- .00055	+ 4
Fa-103	165.00956	34	+ .00058	0	+ .00042	+ 2
Fa-104	164.96445	44	- .00065	- 1	+ .00021	- 2
Fa-105	164.94949	38	+ .00046	0	+ .00014	- 1
Fa-116	175.02918	34	+ .00037	0	+ .00035	+ 2
Fa-117	174.89883	37	+ .00010	- 1	- .00043	- 4
Fa-118	174.89625	39	+ .00041	+ 3	+ .00018	0
Fa-82	188.94369	61	+ .00055	+ 8	+ .00049	+ 9
Fa-83	188.99636	100	+ .00014	+ 9	+ .00002	+ 2
Fa-40	195.97879	110	+ .00011	+13	- .00017	- 4
Fa-44	196.01245	60	+ .00046	+ 9	+ .00070	+ 3

To further check the usefulness of the bridge arrangement the consistency of the bridge was determined by repeating the measurements. Table III shows the results of two measurement runs, the second of which was performed one week after the first. As may be seen, the frequency differences were considerably less than 0.001 percent with only 5 of the 15 measurements exceeding 0.0005 percent. In addition all of the resistance values were well below the 5-ohm or 10-percent desired accuracy.

TABLE III

CHECK OF BRIDGE REPEATABILITY

Crystal No.	Frequency (mc/sec)	R_1 (ohms)	Δf (cycles)	Δf (percent)	ΔR_1 (ohms)
Fa-57	144.99760	52	+ 880	+ .00061	0
Fa-59	144.99511	33	+ 1000	+ .00069	+ 1
Fa-89	154.97008	36	+ 100	+ .00006	- 1
Fa-91	155.02535	30	- 530	- .00034	+ 3
Fa-92	154.98305	31	- 410	- .00027	+ 2
Fa-103	165.00956	34	- 350	- .00021	+ 2
Fa-104	164.96445	44	- 60	- .00003	0
Fa-105	164.94949	38	- 70	- .00004	+ 2
Fa-116	175.02918	34	+ 280	+ .00016	+ 4
Fa-117	174.89993	37	- 740	- .00042	+ 4
Fa-118	174.89625	39	+ 920	+ .00053	+ 2
Fa-82	188.94369	61	- 260	- .00014	+ 3
Fa-83	188.99636	100	- 1000	- .00053	- 2
Fa-40	195.97879	110	+ 620	+ .00032	- 5
Fa-44	196.01245	60	+ 1890	+ .00097	+ 1

It was pointed out in Progress Report No. 3 that the major portion of the coaxial bridge error was due to the inherent unbalance of the basic bridge assembly. To further check this property the crystals were measured in both sides of the bridge and the results compared. These results are shown in Table IV. Although the frequency and resistance differences were small the bridge dissymmetry was verified by the consistent negative frequency and positive resistance errors.

TABLE IV

CHECK OF BRIDGE SYMMETRY

Crystal No.	Frequency (mc/sec)	R_1 (ohms)	Δf (cycles)	Δf (percent)	ΔR_1 (ohms)
Fa-57	144.99760	52	- 620	- .00043	+ 9
Fa-59	144.99511	33	- 250	- .00017	+ 5
Fa-89	154.97008	36	- 450	- .00029	+ 3
Fa-91	155.02535	30	- 270	- .00017	+ 2
Fa-92	154.98305	31	- 220	- .00014	+ 2
Fa-103	165.00956	34	- 600	- .00036	+ 3
Fa-104	164.96445	44	- 460	- .00028	+ 4
Fa-105	164.94949	38	- 400	- .00024	+ 6
Fa-116	175.02918	34	- 750	- .00043	+ 7
Fa-117	174.89883	37	- 1120	- .00065	- 4
Fa-118	174.89625	39	- 750	- .00043	+ 3
Fa-82	188.94369	61	- 60	- .00003	- 1
Fa-83	188.99636	100	+ 40	+ .00002	+10
Fa-40	195.97879	110	- 1390	- .00071	+10
Fa-44	196.01245	60	- 3040	- .00175	- 2

The crystals were also measured in the coaxial bridge at their overtone frequencies in the 200- to 300-mc/sec frequency range. Since no USASEL measurements were available in this frequency range, the results were compared only with those obtained with the Crystal Measurements Standard. The frequency differences obtained were well below 0.001 percent in all but two questionable cases. However, considerable disagreement in resistance measurements was obtained, especially above 250 mc/sec. As of this report date an investigation of the possible causes of these discrepancies had not been made but additional measurements of crystal parameters and VHF Rheostat impedances are planned. A study of the bridge reaction to possible high frequency crystal equivalent circuits will also be made in an effort to determine the basic reasons for the resistance differences.

The results obtained with the coaxial bridge over the 100 to 200 mc/sec frequency range indicate that the presently obtainable accuracy is comparable with that of other available methods. In the 200- to 300-mc/sec range some question still remains as to the accuracy, particularly in respect to the crystal resistance measurements. Although additional efforts will be made to determine the causes of these resistance measurement discrepancies, the general accuracy and overall suitability are such that the bridge appears satisfactory for use in connection with the oscillator circuitry under development.

2. Experimental Oscillators

When the Crystal Parameter Bridge technique is used with an active oscillator, the frequency control is maintained by the crystal impedance variations near resonance as modified by the bridge configuration. In effect the crystal characteristic as presented to the oscillator is degraded by the shunt arm of the bridge. In particular, a maximum impedance change of two to one is imposed, near bridge balance, by the variable rheostat of the shunt arm.

This impedance degradation, as discussed in Progress Report No. 3 is the major factor which prevented satisfactory operation of the Plate Degenerative Oscillator when used with the Coaxial Crystal Parameter Bridge. Additional experimental tests were made on this oscillator by utilizing passive elements in place of the crystal and bridge. These tests have confirmed the suspected inability of the Plate Degenerative Oscillator to oscillate satisfactorily with a maximum impedance change of only two to one. This was found to be true regardless of the phase angle considerations.

The bridge degrading property therefore necessitated an investigation of additional oscillatory circuitry which would not only meet the original requirements set forth in Progress Report No. 1 but would in addition be more sensitive to the phase and impedance changes exhibited by the bridge-crystal combination. Of the possible configurations only those which permitted one terminal of the crystal unit to be grounded and which permitted simple capacitive neutralization of C_o were considered.

One configuration which appeared to meet these requirements was the capacitance bridge oscillator described in Progress Report No. 2. Two additional experimental models of this oscillator were constructed during the present report period. The construction of the first model which is shown schematically in Figure 18 was similar to that of the original in that it utilized a 2-in. hairpin loop for the primary and a 1-in. loop for the secondary. These loops, however, were made physically wider in order to aid in reducing the cross coupling effects that were observed in the first model. A Faraday shield between the two loops was also utilized to prevent capacitive cross coupling. A Western Electric 417A tube which has a rated transconductance of 25,000 micromhos was used in the grounded grid amplifier. Crystal controlled oscillations could be obtained throughout the 200- to 300-mc/sec frequency range of the tuned circuit provided the C_o of each crystal used was individually neutralized.

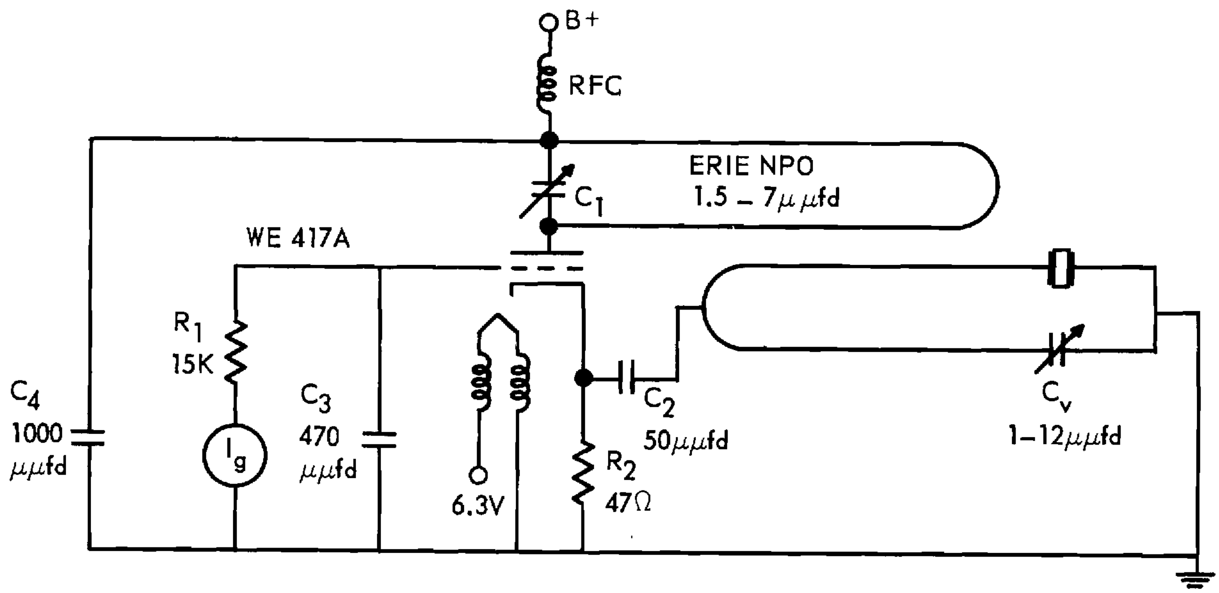

Figure 18. Capacitance Bridge Oscillator.

In order to determine qualitatively the sensitivity of the oscillator to the resonant characteristics of a bridge-crystal combination, a shunt resistance of 30 ohms was placed across the crystal. This resistor in effect simulated the degrading property that would be exhibited by the Coaxial Crystal Parameter

Bridge. Under this condition crystal controlled oscillations could still be obtained throughout the 200- to 300-mc/sec frequency range.

In its present form two practical considerations prevent a further analysis of this circuit when used with the Coaxial Crystal Parameter Bridge. The first is the tuning capacitor C_1 whose $\frac{1}{2}$ turn of adjustment for the entire 200- to 300-mc/sec range makes tuning very difficult. The second is the physical arrangement which is such that the coaxial bridge cannot be conviently connected in the circuit. It is contemplated that additional models will be constructed which will eliminate these two difficulties and permit a more complete analysis of the circuit to be made.

A second experimental model of this same basic configuration was constructed which utilized a modified Mallory UHF inductuner (shorted line) tunable from approximately 350- to 430-mc/sec. The modification consisted of placing two mirror image lines back to back in a manner such that mutual coupling could be obtained and such that both lines could be adjusted simultaneously. A copper foil Faraday shield was inserted between the lines and the oscillator components were mounted directly on the inductuner frame. The schematic diagram is essentially that of Figure 18 except a type 6AN4 tube was utilized and the tuning capacitor C_1 was eliminated. Crystal controlled oscillations were obtained at frequencies as high as 420 mc/sec with this oscillator. C_o neutralization could be accomplished in most cases although the capacity required was considerably less than expected. Several crystals were tried with this oscillator and satisfactory operation was obtained in the majority of the cases. In particular the crystals of Table V were oscillated at the frequencies and overtones indicated. Complete C_o cancellation could not be obtained with Crystal

No. 1-3 at 353 mc/sec but lock-in oscillations were obtained. C_o cancellation was complete, however, from slightly above 355 mc/sec to well beyond the next overtone oscillation of this particular crystal which occurred at 400 mc/sec. Although very little is known at the present time regarding the frequency controlling properties of crystals at these overtones, it is of interest to note the position of these particular crystal responses on the Smith charts presented in the appendix. The proximity of these responses to the higher conductance portion of real axis appears to be significant and indicates the need of further investigation.

TABLE V

CRYSTALS OPERATED IN CAPACITIVE BRIDGE OSCILLATOR

Crystal No.	Fundamental Frequency (mc/sec)	Oscillating Frequency (mc/sec)	Overtone
1-3	23.5	353	15
Fa-44	28	364	13
3-W	25	375	15
Fa-59	29	376	13
Fa-118	35	382	11
Fa-91	31	403	13
1-3	23.5	400	17
Fa-44	28	420	15

VI. CONCLUSIONS

Calibration data and actual crystal measurement data indicate that the best accuracy presently obtainable with the Crystal Measurements Standard is about 5 percent for impedance magnitude and $\pm$ 4 degrees for phase angle. This is obtained by using a General Radio Type 1602-B Admittance Meter with a half-wavelength transmission line between the meter and the crystal. This accuracy is possible only under ideal conditions and only for certain crystals. The accuracy is limited principally by the accuracy of the Admittance Meter. Because of the poor condition of the available Admittance Meter, a new instrument would probably give a considerable improvement in accuracy.

Investigations concerning the presently used crystal equivalent electrical circuit indicated that the circuit does not satisfactorily represent all crystals at high frequencies. In particular, the need for a capacitance, C_o', directly across the pin of the crystal holder is indicated. This study did not progress sufficiently to assert definite conclusions concerning the other elements of the equivalent circuit.

Numerous measurements on actual high frequency crystals resulted in close frequency agreement between the Crystal Measurements Standard, the Coaxial Crystal Parameter Bridge and other measurement methods. Measurements of equivalent resonant resistance did not provide the agreement anticipated. Disagreements in both frequency and resistance can possibly be accounted for by the lack of standardization of the method of cancelling C_o with different measurement systems. Such standardization is practical only by first arriving at a satisfactory equivalent circuit.

A comparison with other power measurements indicated the prototype thermistor-bridge power meter to be capable of measuring r-f power in the range from 0.5 mw to 4.0 mw with an accuracy of $\pm$ 5 percent. Better matching of the two thermistors and improvement in the bonding between the thermistor and dissipating body should permit lower values of r-f power to be measured with the desired accuracy.

An experimental capacitance bridge oscillator was constructed that demonstrated an ability to maintain crystal controlled oscillations under conditions similar to those imposed by the Coaxial Crystal Parameter Bridge. A modified physical arrangement which will accept the coaxial bridge will be required in order to fully determine the capabilities of this configuration. Crystal controlled oscillations were obtained with a similar configuration at frequencies as high as 420 mc/sec. The present inadequate knowledge of the frequency controlling properties of crystals at these overtones reveals the need for further investigation of the results obtained.

VII. PROGRAM FOR NEXT QUARTER

Work during the next quarter will be a continuation of that reported in the preceding pages with emphasis on the following objectives:

1. perform additional tests of the prototype crystal power measuring system to determine its accuracy;

2. continue the investigation of oscillator circuits for use with the Coaxial Crystal Parameter Bridge;

3. procure and evaluate new GR admittance meters and HP UHF bridges for use in the Crystal Measurements Standard; and

4. investigate additional commercial equipment for use in the Crystal Measurements Standard.

Submitted by:

Douglas W. Robertson
Project Director

Approved by:

W. B. Wrigley, Head
Communications Branch
of the
Physical Sciences Division

VIII. PERSONNEL

Biographical sketches of the key technical personnel were included in Progress Reports No. 1 and 2. The time contributed by each during the present period is:

Douglas W. Robertson	Project Director	Full Time
Samuel N. Witt, Jr.	Research Engineer	2/3 Time
William R. Free	Asst. Research Engineer	Full Time
James E. Lane	Technical Assistant	1/2 Time

IX. APPENDIX

A. Addendum

Figure 15, page 33 of Progress Report No. 3, has been found to be in error. The scale on the R_1/R_2 Ratio (abscissa) was inadvertently shifted two grid divisions. The first grid line should be labeled 0.5 rather than 0, the third line should be 1.0 instead of 0.5, 1.0 should be 1.5, etc. With the corrected scale, the K factor obtained for an R_1/R_2 ratio of 1 is .675 (actual point) which corresponds very closely with the power ratios of Tables I and II (first bonding condition) of that report.

B. Admittance Characteristics of Measured Crystals

This section contains 15 figures. Refer to page v, LIST OF APPENDIX FIGURES, for a listing of the crystals that were measured.

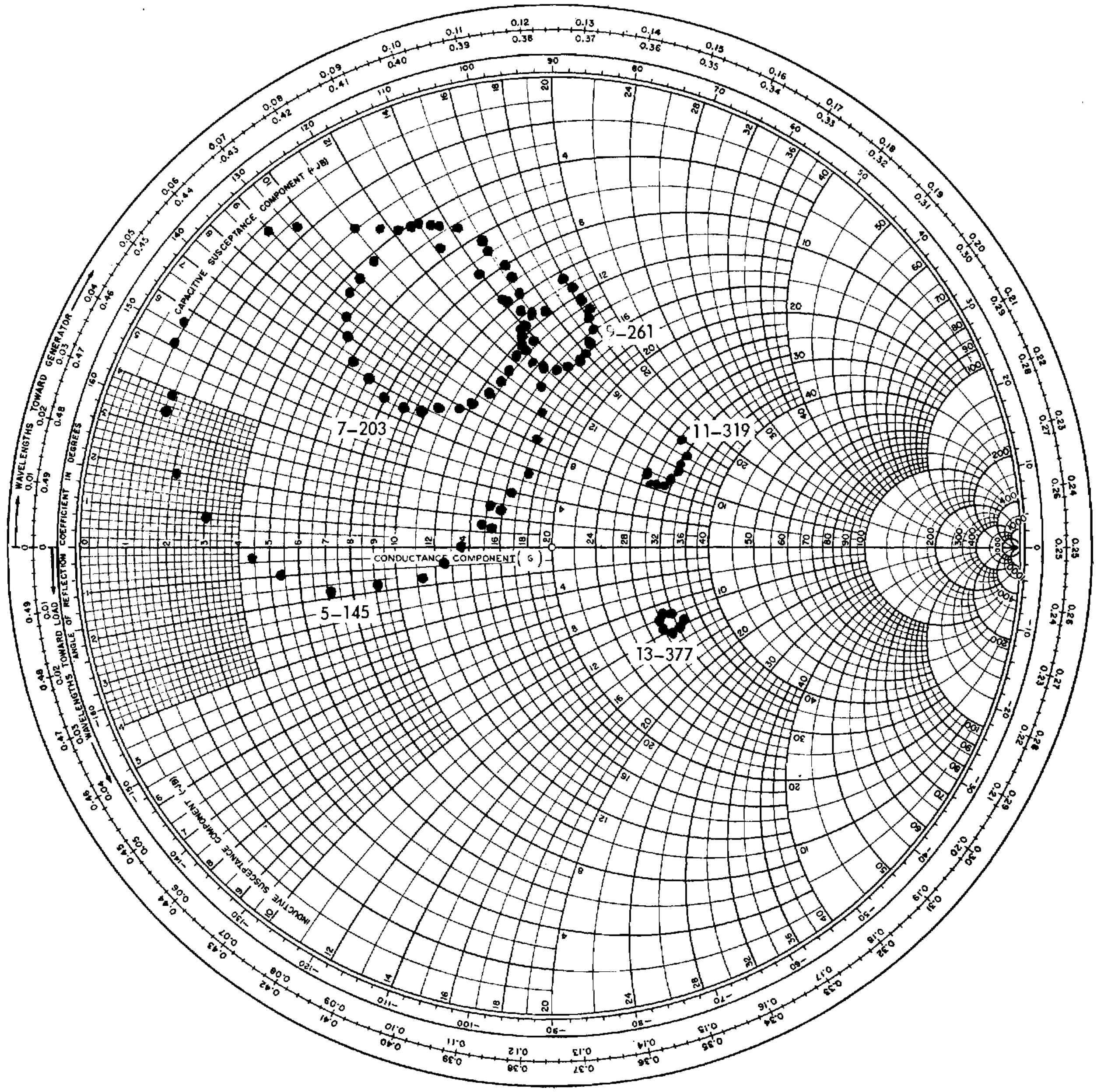

Figure A-1. Admittance Characteristics of Cryatal No. Fa-57.

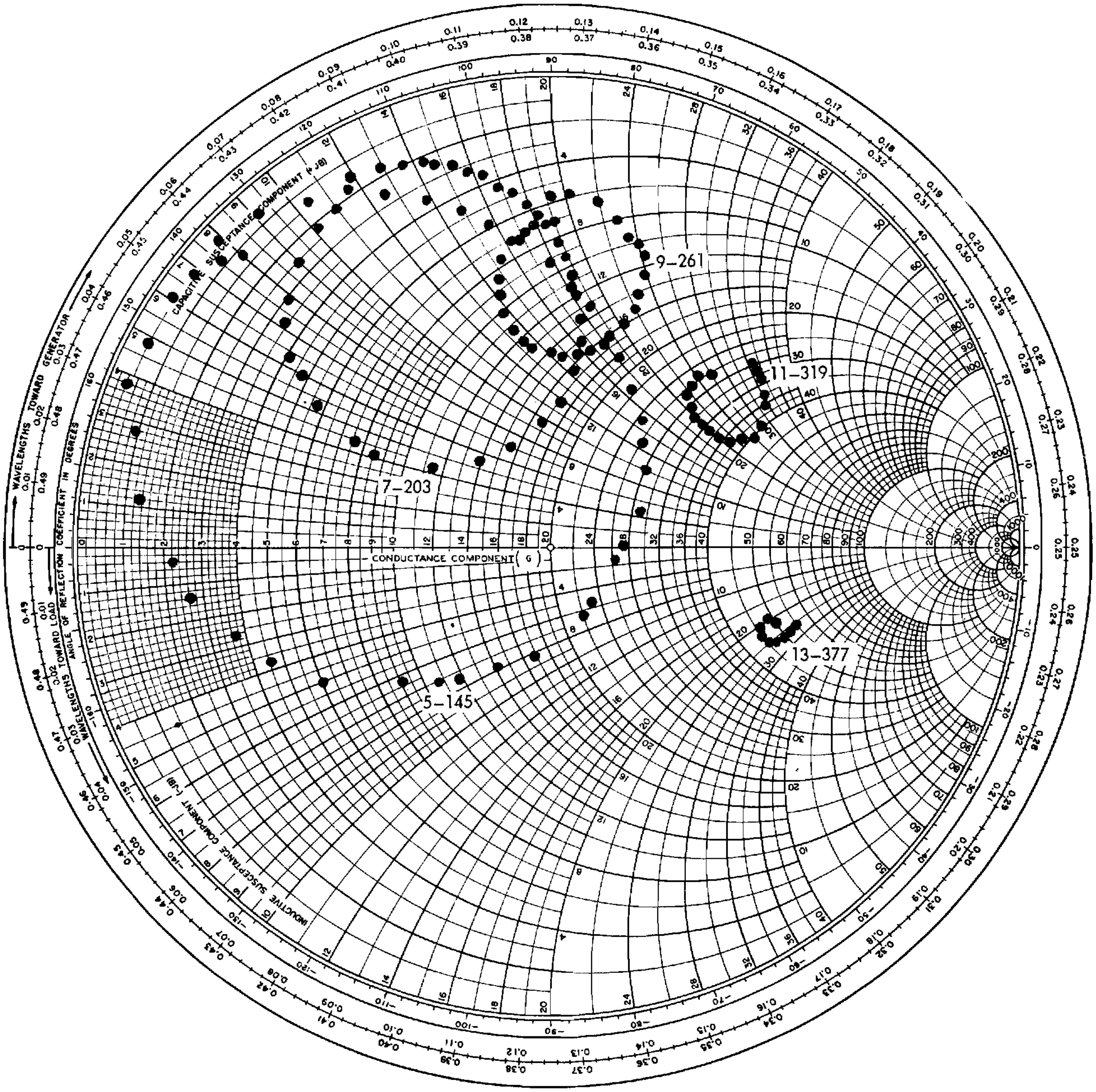

Figure A-2'. Admittance Characteristics of Crystal No. Fa-59.

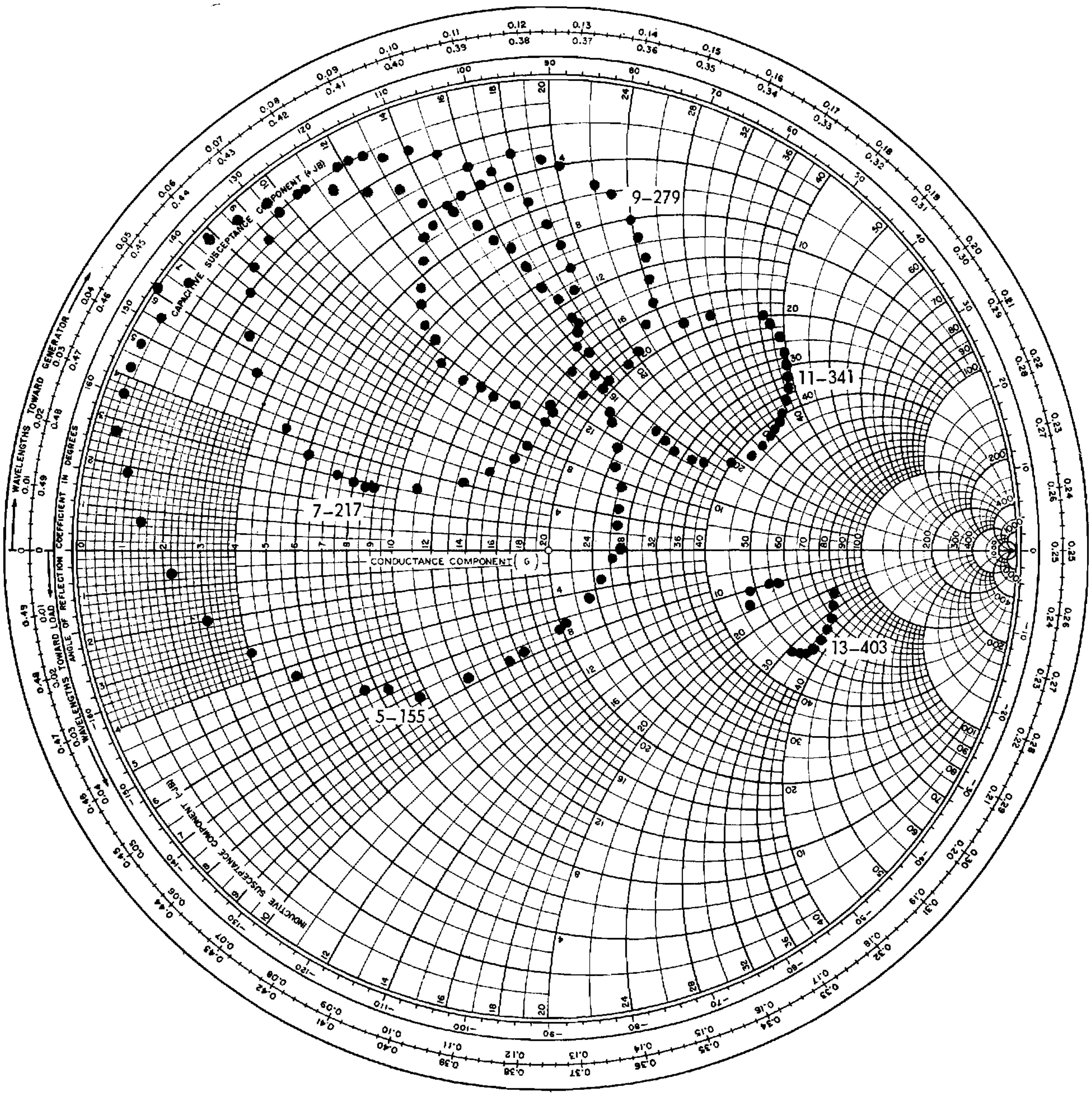

Figure A-3. Admittance Characteristics of Crystal No. Fa-89.

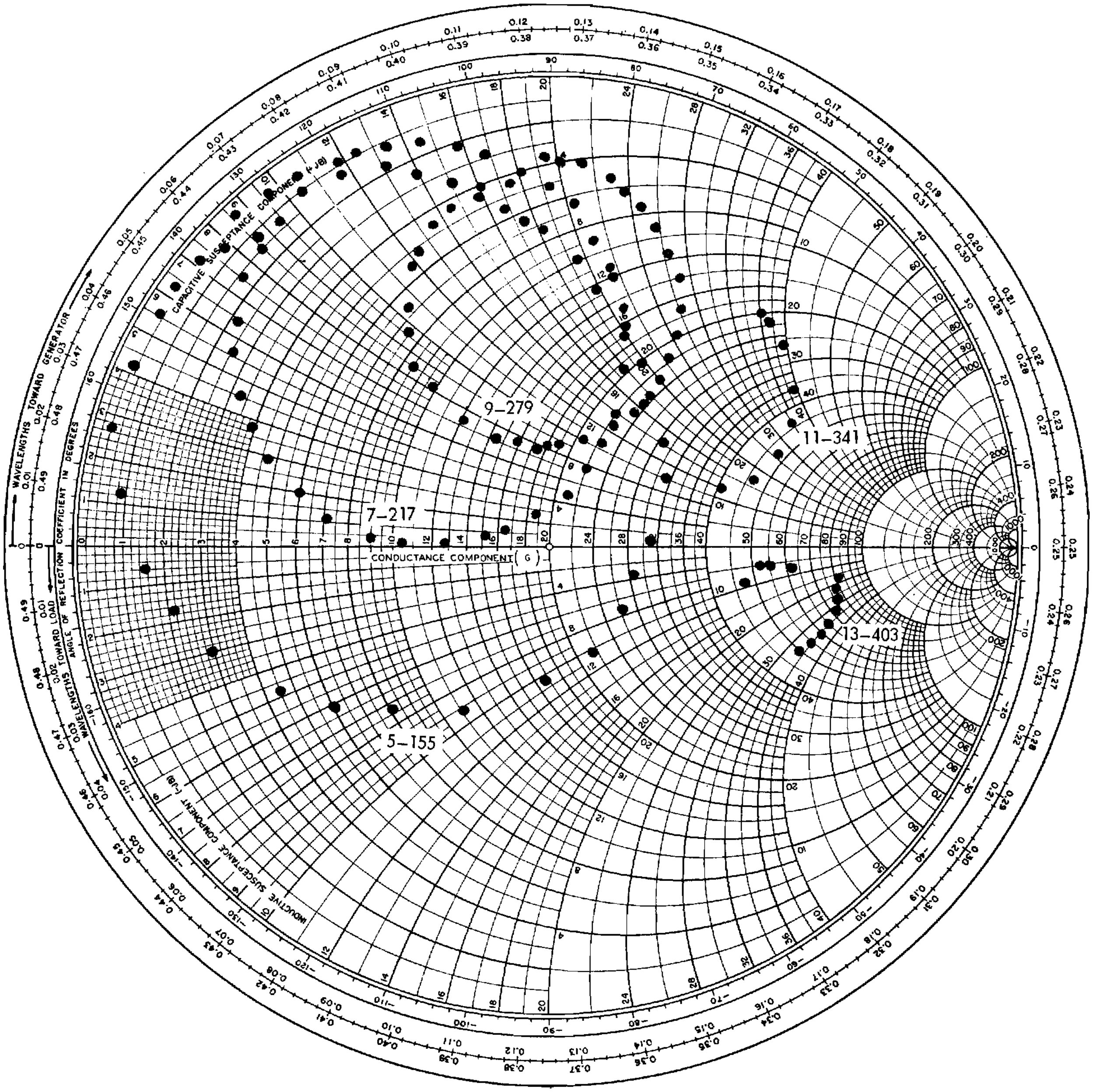

Figure A-4. Admittance Characteristics of Crystal No. Fa-91.

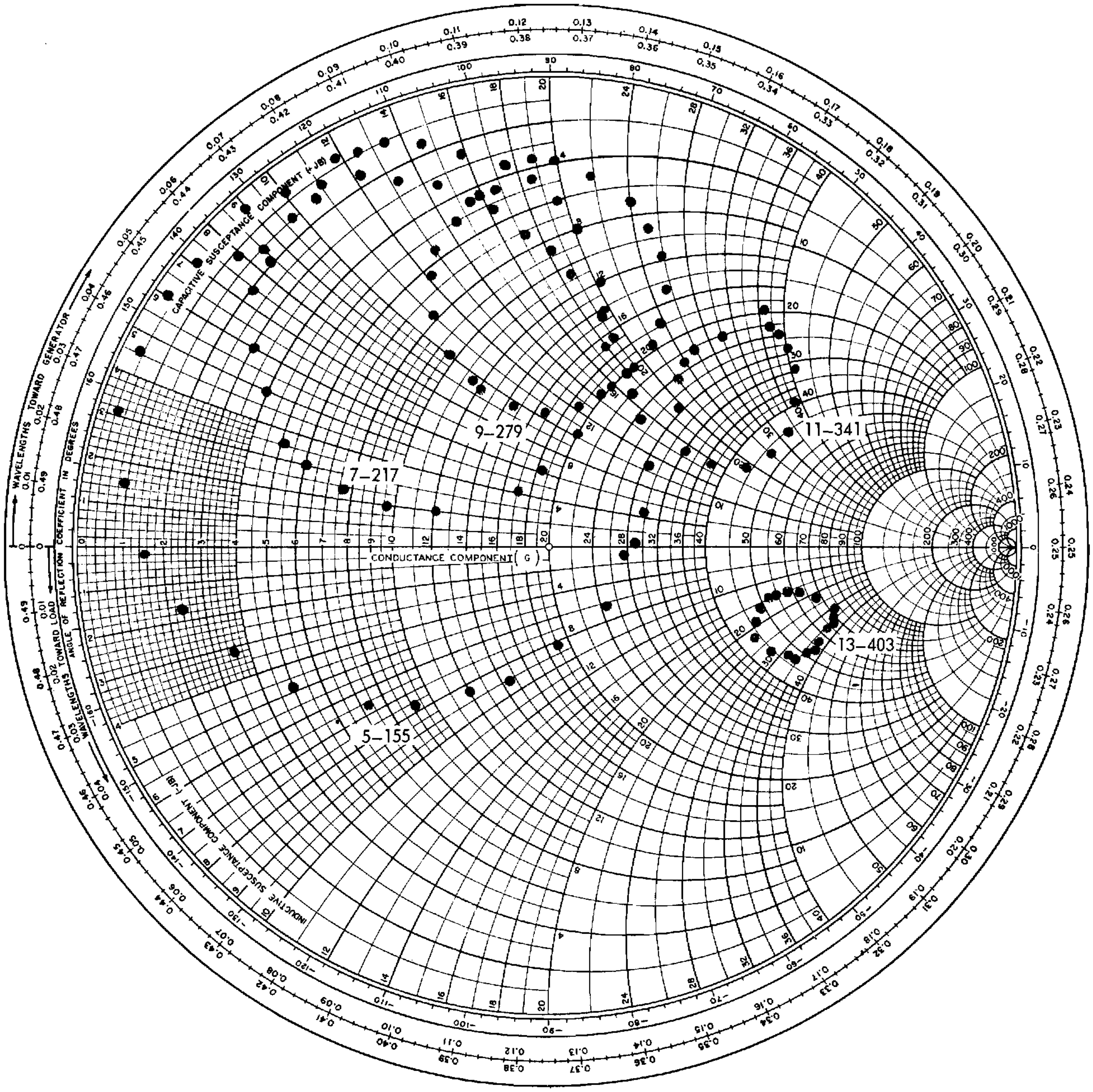

Figure A-5. Admittance Characteristics of Crystal No. Fa-92.

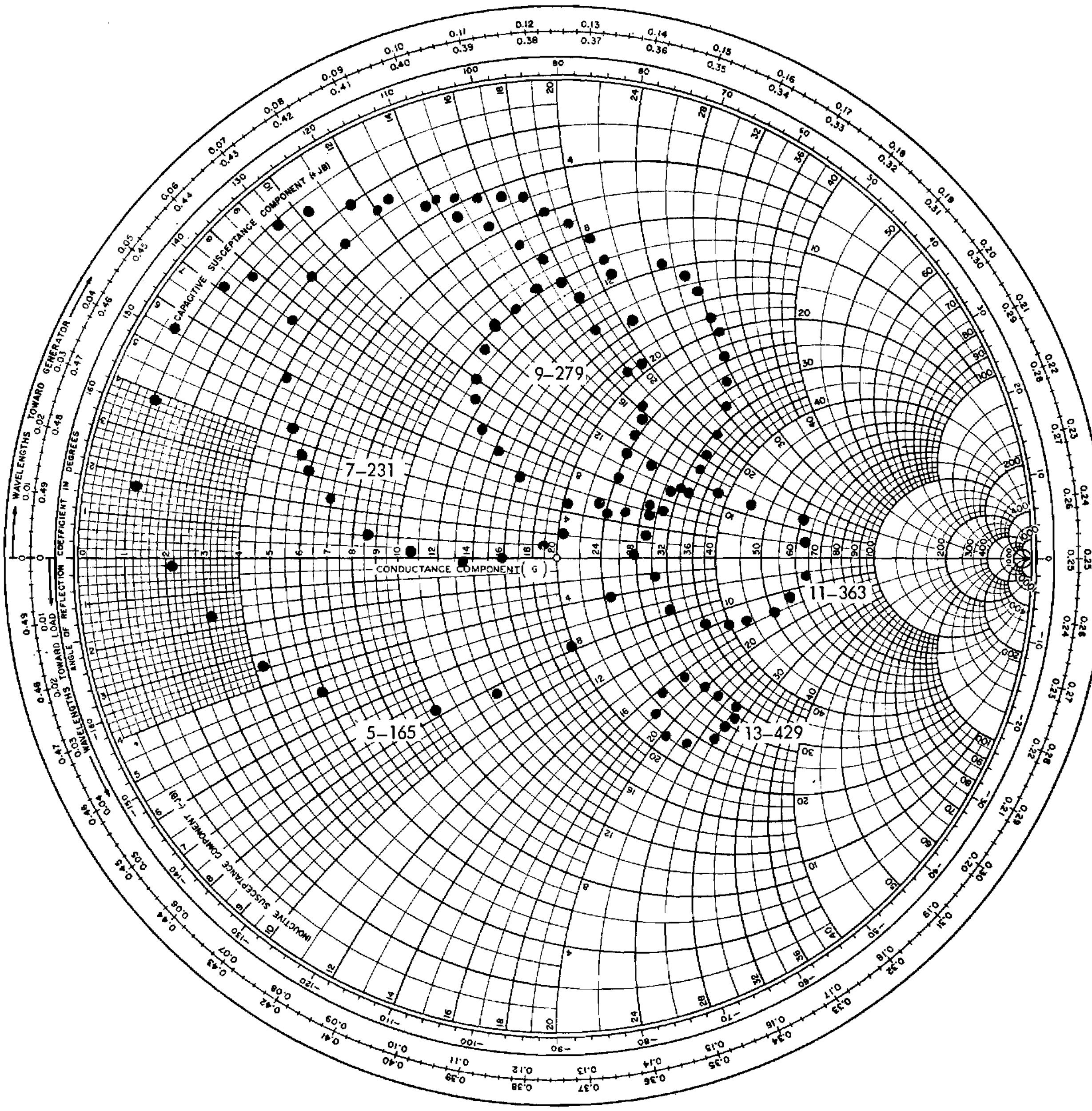

Figure A-6. Admittance Characteristics of Crystal No. Fa-103.

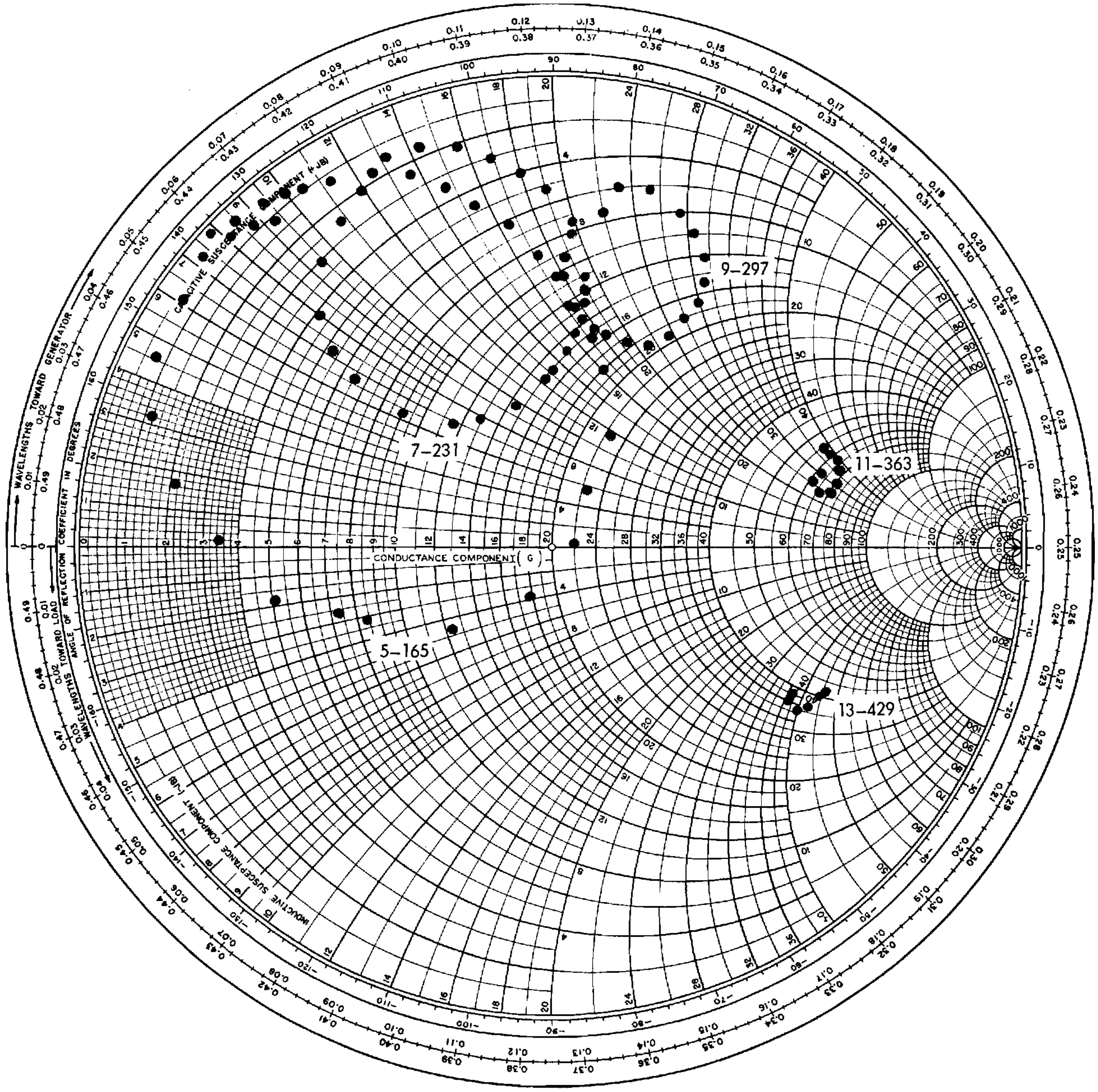

Figure A-7. Admittance Characteristics of Crystal No. Fa-104.

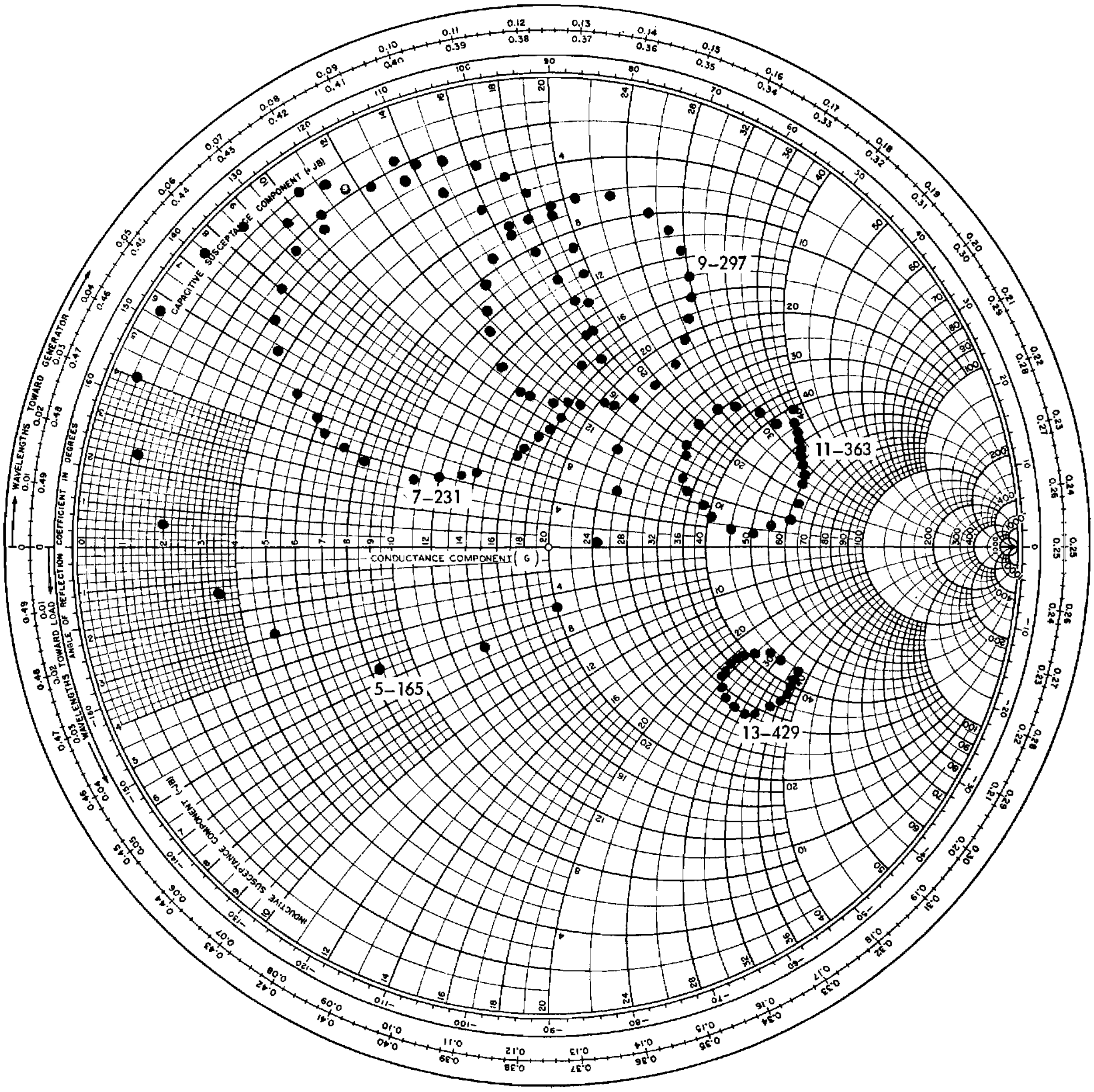

Figure A-8. Admittance Characteristics of Crystal No. Fa-105.

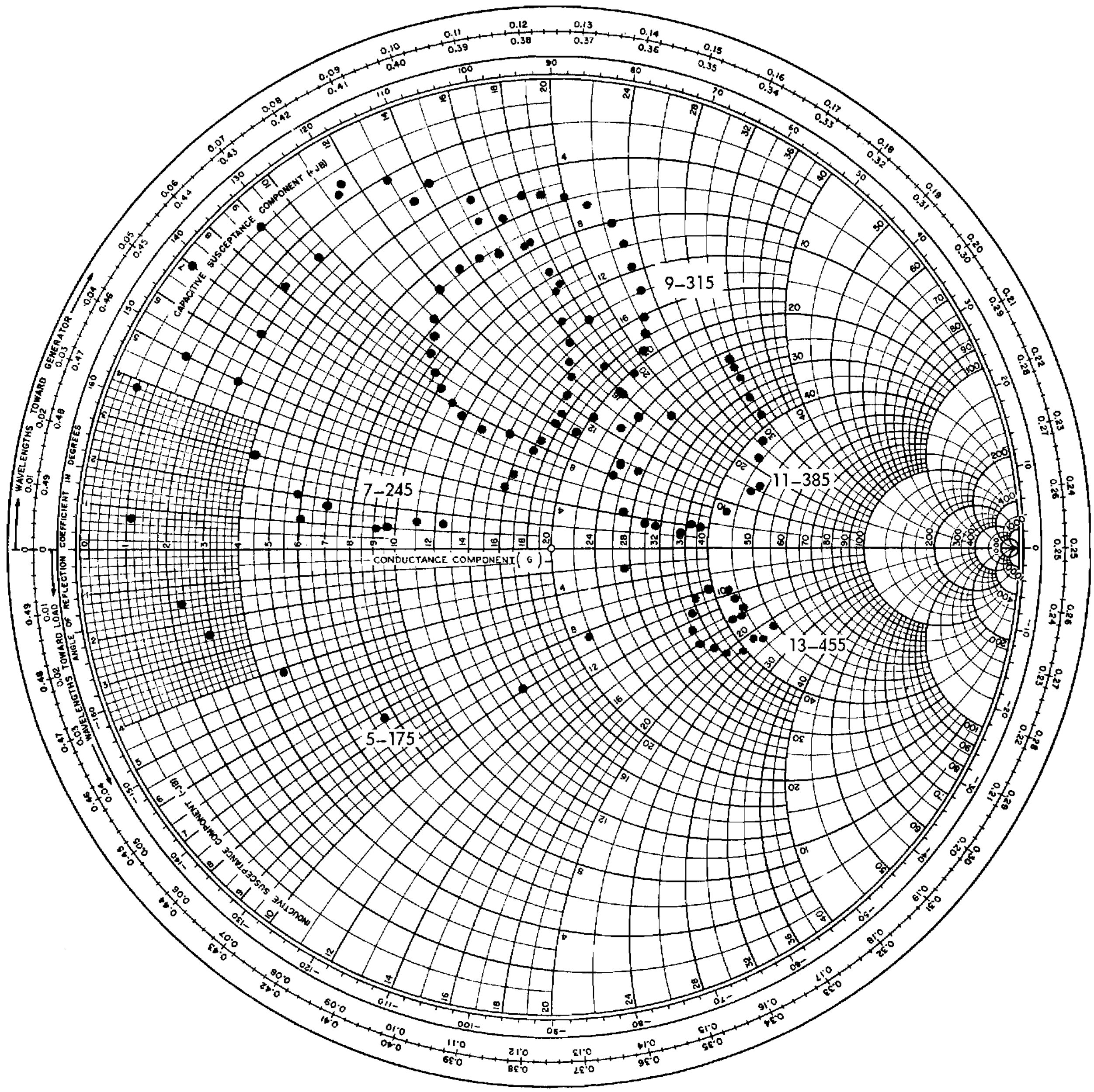

Figure A-9. Admittance Characteristics of Crystal No. Fa-116.

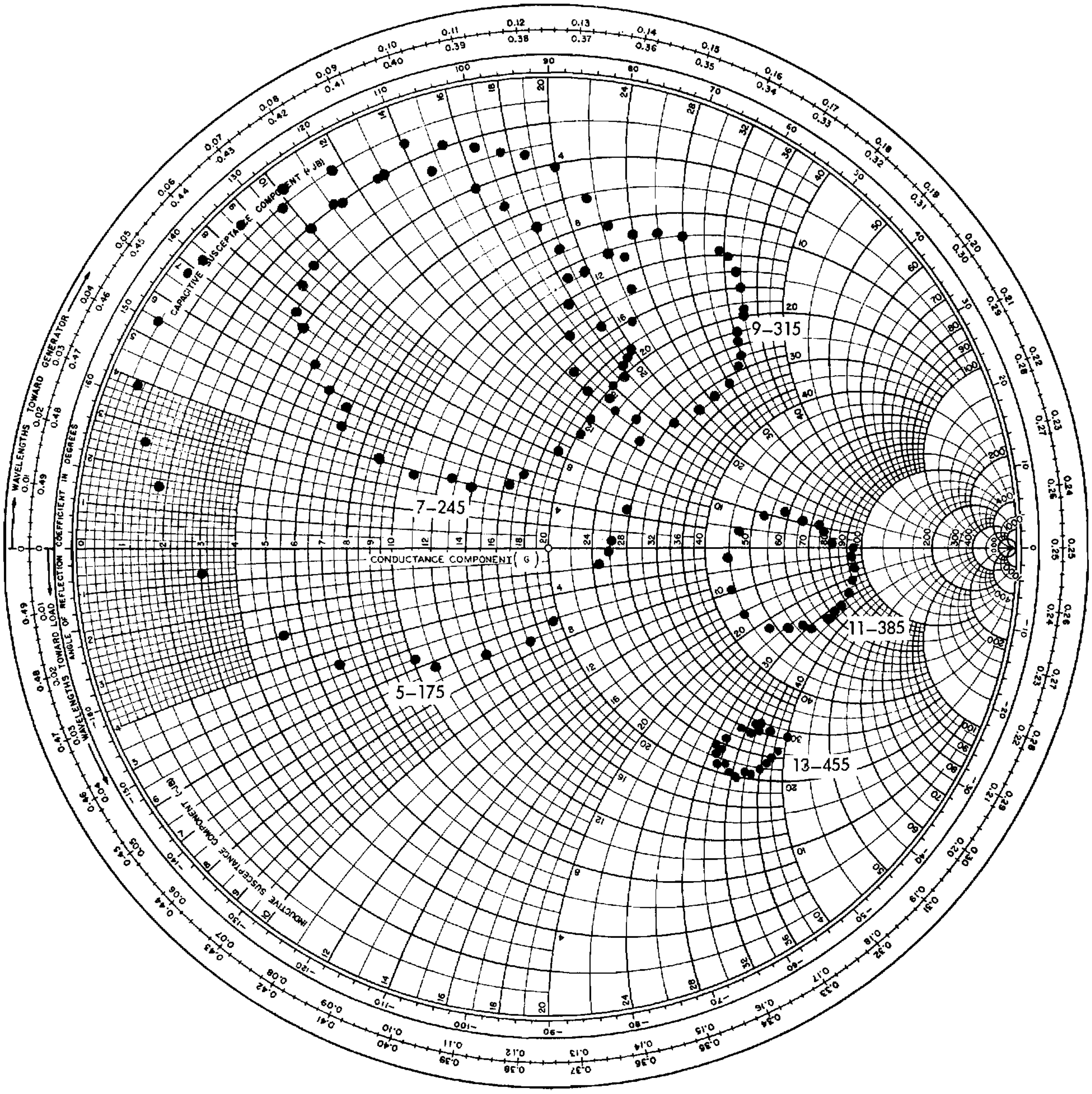

Figure A-10. Admittance Characteristics of Crystal No. Fa-117.

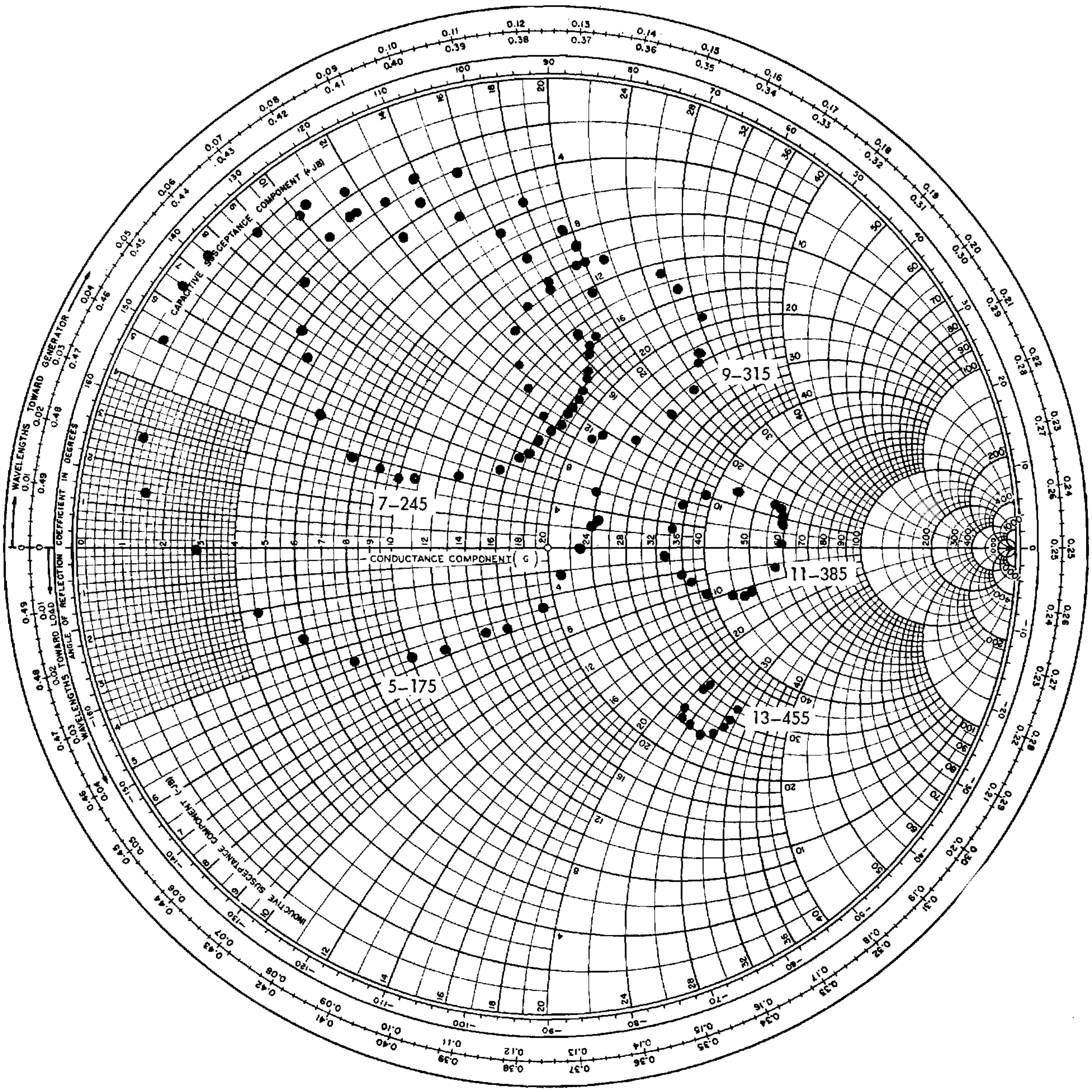

Figure A-11. Admittance Characteristics of Crystal No. Fa-118.

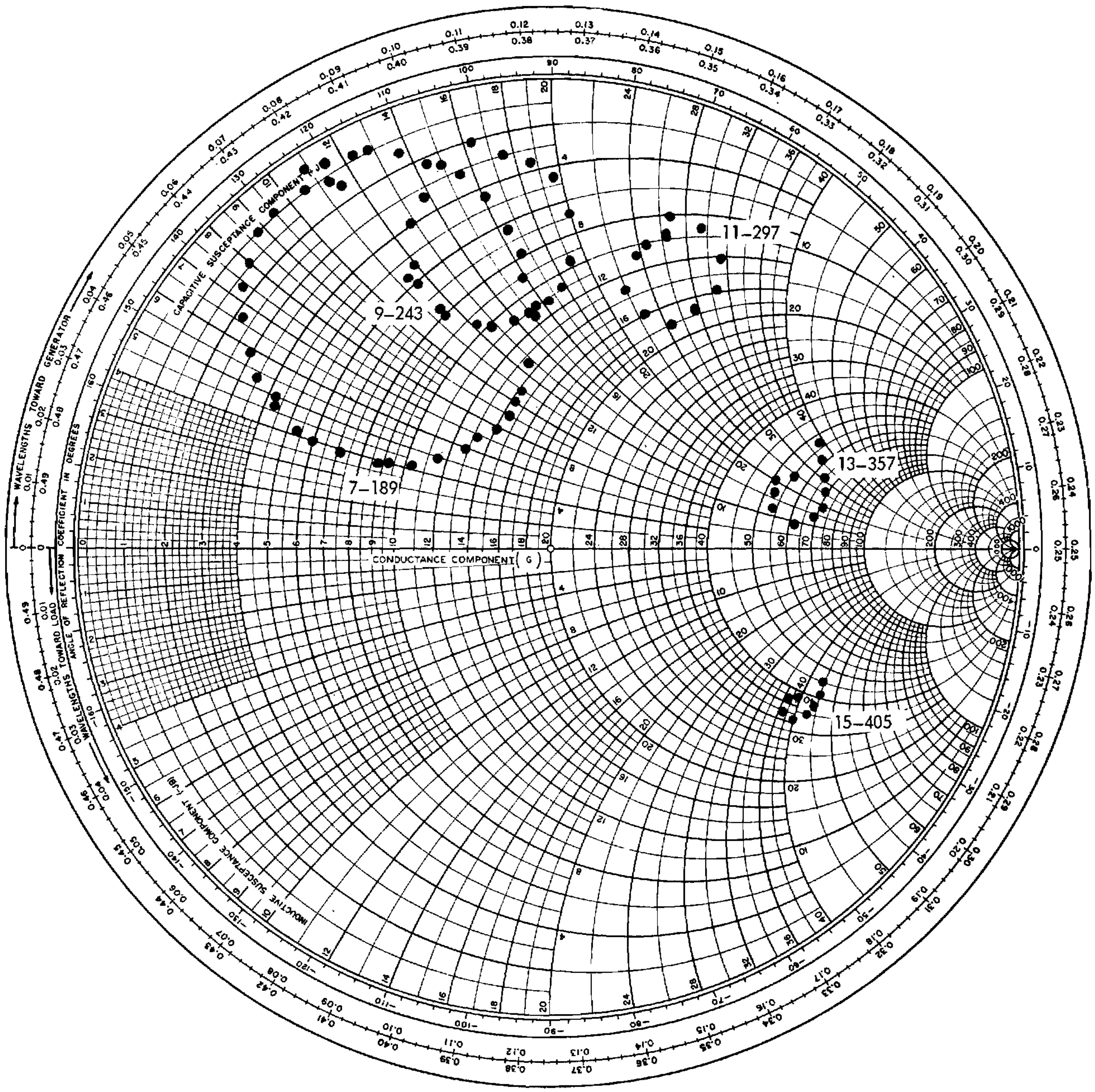

Figure A-12. Admittance Characteristics of Crystal No. Fa-82.

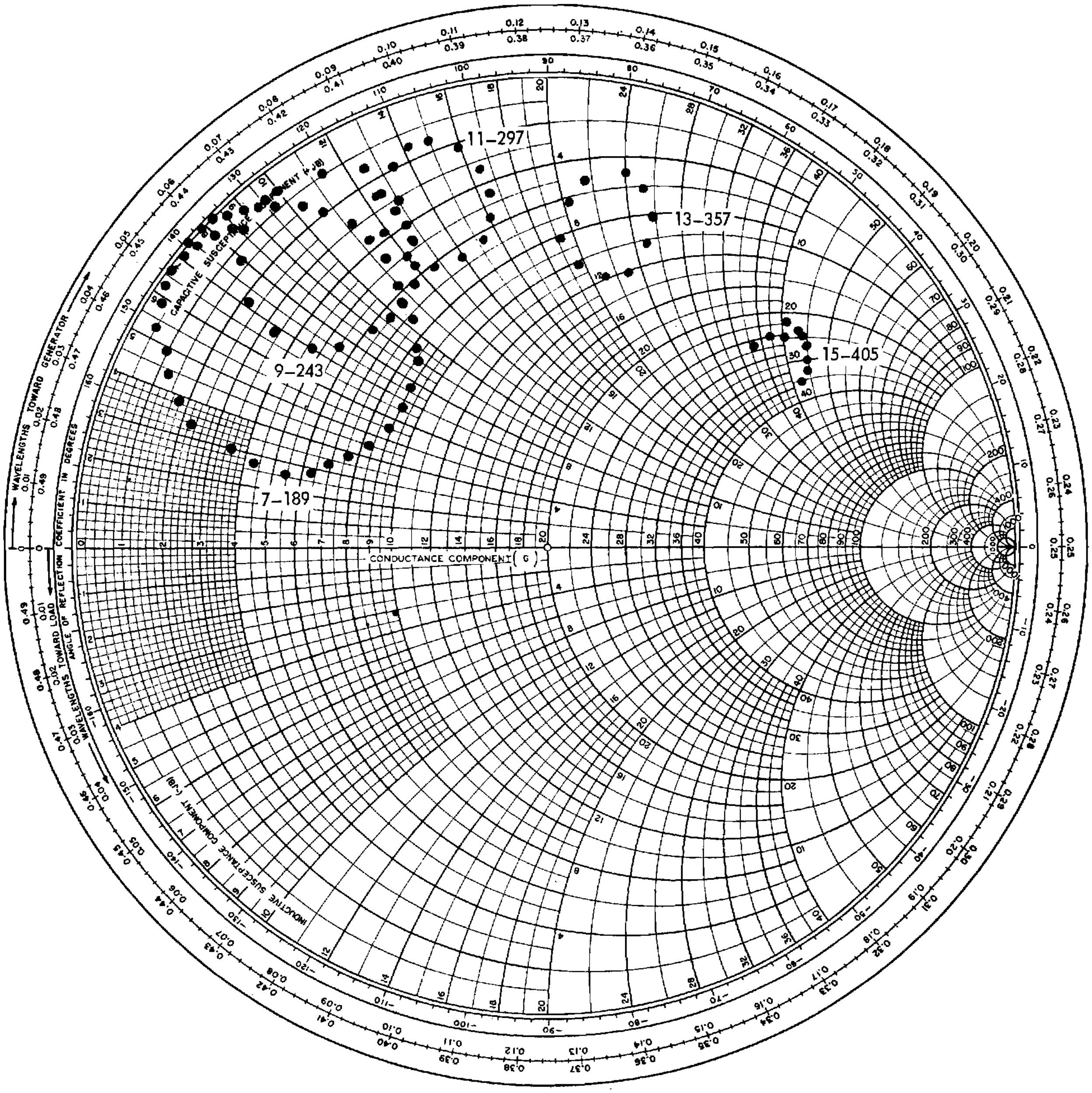

Figure A-13. Admittance Characteristics of Crystal No. Fa-83.

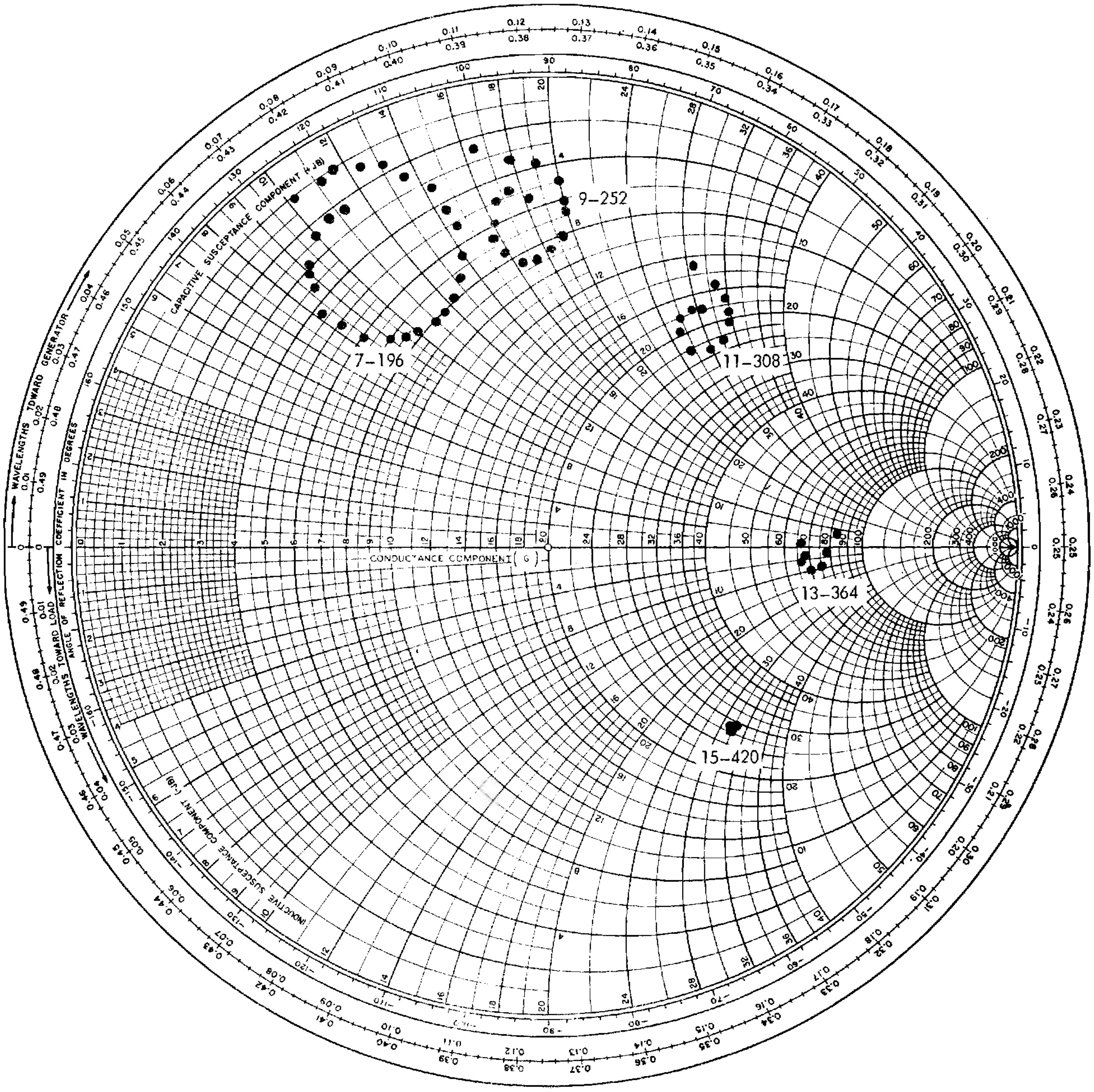

Figure A-14. Admittance Characteristics of Crystal No. Fa-40.

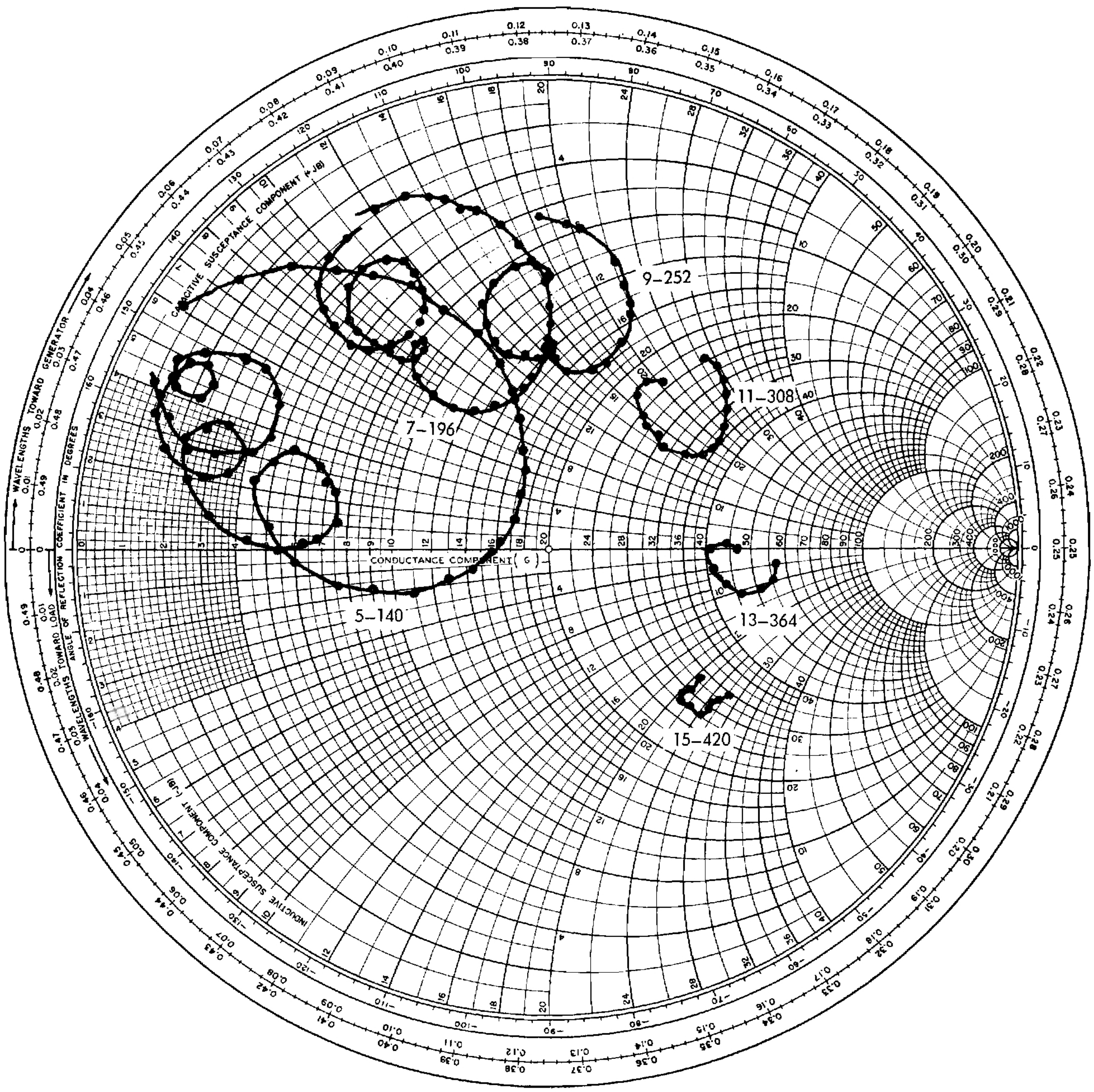

Figure A-15. Admittance Characteristics of Crystal No. Fa-44.